ARTILLERY AND EXPLOSIVES

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ARTILLERY AND EXPLOSIVES

ESSAYS AND LECTURES WRITTEN AND DELIVERED AT VARIOUS TIMES

548

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WITH
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PREFACE

Some apology is certainly due for the republication of the Papers and Lectures which appear in this volume, but I have been asked so often, chiefly by foreign friends, for papers which were out of print that I at last thought it better to republish.

But here again I was placed in a position of some difficulty, for the Papers, having been published at intervals during a period of nearly fifty years, had necessarily from their nature a good deal of repetition, and I soon found that, were I to attempt to remove this defect, I should have practically to rewrite the whole volume.

I, therefore, decided that it was better to republish the Papers precisely as they were written or delivered, and it may be that this decision has certain advantages.

Extraordinary as has been the advance in every department of Science during the long reign of Queen Victoria, the progress in Naval and Artillery Science has been no less remarkable.

When I entered the Service, the line-of-battle ships were all sailing vessels, and their armaments and appliances differed but little, except as regards size, from those in use in the days of Henry VIII. and of Queen Elizabeth. Mechanical contrivances the older Officers would not hear of, and I have heard more than one declare that no contrivance should be allowed on board a man-of-war which could not be handled and repaired by the Blue Jackets, who had proved the efficiency both of men and material in so many victorious actions.

The same spirit influenced the older Peninsular and Waterloo Officers of my own Corps, the Royal Artillery, and I remember an occasion when it was curiously shown. After the introduction of Rifled Artillery a dinner was given by the Royal Artillery Mess at Woolwich to the late Lord Armstrong. It was the duty of the

President to propose the health of the guest of the evening, which was gracefully done, but after describing what had been effected by Sir W. Armstrong, the orator concluded, "but for myself I am radically opposed to any change."

The feeling to which I have referred lasted a considerable time, and led to some retrograde steps, such as the abandonment, for a season, of breech-loading guns, and it led also to England being for a time behind the principal Continental nations from the refusal to adopt improvements until (which will never happen) perfection and finality were reached.

Having entered the Service when Rifled Artillery was not thought of, having served as Secretary to the Committee which introduced Rifled Artillery, and having been more or less connected with all the great changes which have taken place, both as regards the guns, their mountings, equipments, and propellants, it may be that the present volume gives, in some respects, a not uninteresting history of the immense changes that have taken place in the Naval and Land Service Armaments.

It is not perhaps wonderful that the Officers of both Services, who had taken part in the great land and sea battles of the beginning of last century, should have looked with distrust upon radical changes, and should have insisted upon the sufficiency of the weapons which had served them so well.

To illustrate the distrust with which novelties were regarded, I may mention that I was Secretary to a Committee, which had its meetings at the War Office, called, I think, the Committee on Plates and Guns, and at their meetings were discussed, among other things, the details of the gun intended to be the heavy gun for both Land and Sea Service. The Artillery Officers pressed for a gun weighing 7 tons, but the Naval Officers were doubtful whether so heavy a gun could be carried on board ship. The disputed point was compromised by making the gun 6½ tons, but as strong doubts were expressed as to whether rifling would be successful in such a gun, the calibre was finally ordered to be such that it would fire 100-lb. spherical shell if the gun were unsuccessful as a rifled gun. Twenty of these guns were actually made, and were called, if I remember rightly, the Somerset Gun; the Duke of Somerset being then the First Lord of the Admiralty.

The objections to anything like a mechanical contrivance were, as I have mentioned, very strong, especially among some of the older Officers, who could hardly be got to look with patience upon any appliance to which they were not accustomed.

All this is now changed. A modern battleship, as I have

pointed out, carries well on to a hundred machines of a very varied, and, in some cases, of a most complicated, character.

The country may well be proud of the ability and zeal with which the Naval Officers of the present day have mastered, and the skill with which they use, the varied machinery committed to their charge, and while the energy and zeal which pervades all ranks endure, we may be satisfied that the traditions which have been handed down to us through many generations of great sailors, will not be departed from, and, should occasion arise, that fresh lustre will be added to, the records of the Navy.

A. N.

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Page 39, line 7, *for* "Plate II., Figs. 1 and 2," *read* "coloured diagram, Figs. 1 and 2, p. 32"

" 40, line 13, *for* "Plates III., IV., and V, p. 32," *read* "coloured diagrams, Figs 3, 4, and 5, p. 32"

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I.

ON THE APPLICATION OF THE THEORY OF PROBABILITIES TO ARTILLERY PRACTICE.

(*Royal Artillery Institution Papers*, 1858.)

DURING the investigations of the Special Committee on Rifled Cannon, it became a point of considerable importance to be able to obtain, with somewhat more accuracy than could be done from a mere inspection of tables of practice, the relative precision of fire of the various guns submitted for report.

The plan I adopted for this purpose, with the approval of the Committee, was to calculate for each gun the area within which it was an equal chance that any one shot would strike; or, as it may otherwise be expressed, that area within which, if a given number of shots were fired, half of that number might be expected to fall. This area I termed the probable rectangle, and, by calculating it for various guns, we are enabled to form a definite opinion as to their comparative accuracy.

Before, however, entering upon the details of the particular plan adopted, it may not be out of place, and may tend to clearer views on the subject, to give a short account, simplified as much as possible, of the celebrated method upon which that plan is founded.

Experience shows that observations, no matter of what kind, when repeated under what we call "precisely similar circumstances," do not give us results exactly the same, but results differing from one another in a greater or less degree, or as we term it, we have observations more or less accurate. The causes of these variations are unknown to us, or if we do know some of their causes, at all events the law according to which the errors occur is unknown; for if we know both the cause of an error and the manner in which it occurs, such an error is at once removed from the domain of chance. In

artillery practice, for instance, we are able at once to assign several causes which account for variations of fire (*e.g.*, variable strength of powder, variable rotation of the projectile, windage, etc., etc.); but as we do not know the law according to which these causes affect the flight of the projectile, errors induced by them must be treated in the same manner as errors of observation.

Two assumptions are made with reference to the causes of error—(1) "That in a given kind of observation, both the number of the sources of error and the number of combinations of which they are capable remain the same"; and (2) "That the same combination when it occurs produces the same error." Although we are in ignorance both as to the number of the combinations of the various causes of error, and as to the number of the combinations which produce equal errors, yet if we have, in a series of observations, a certain system of errors, we may, knowing the proportion in which errors of various magnitudes have appeared, calculate the probability of their reappearance in another set of similar observations.

Let us assume the probability of an error Δ to be $\phi(\Delta)$. Now, by the probability of any error, we understand the ratio which the number of combinations producing this error bears to all possible combinations, so that in a series of m observations—m being so large that we may conclude that all errors have occurred in their due proportion—if m' observations are affected with the error Δ, we have

$$\phi(\Delta) = \frac{m'}{m} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

or $m\phi(\Delta)$ = number of observations affected with the error Δ. In the same way, $m\phi(\Delta')$ represents the number of observations affected with the error Δ', $m\phi(\Delta'')$ the number of those affected with Δ'', and so on, till we include all errors from $+\infty$ to $-\infty$, and hence we have the equation

$$m\phi(\Delta)+m\phi(\Delta')+m\phi(\Delta'')+, \text{ etc.} = \text{whole number of observations} = m$$
$$\text{or} \qquad \phi(\Delta)+\phi(\Delta')+\phi(\Delta'')+, \text{ etc.} = 1 \quad . \quad . \quad (2)$$

Now, since Equation (2) contains the probabilities of all errors from zero to $\pm\infty$, it is evident that if we suppose Δ to vary continuously, the probability of any determinate Δ must be infinitesimal; the probability then of an error occurring between the error Δ and the infinitely near error Δ', or as we may write it

$\Delta+d\Delta$, will be $\phi(\Delta)d\Delta$, or in the language of the integral calculus, Equation (2) is equivalent to

$$\int_{-\infty}^{+\infty}\phi(\Delta)d\Delta=1 \quad . \quad . \quad . \quad . \quad (2')$$

which simply means that the probability of an error between $+\infty$ and $-\infty$ = unity or certainty.

We must now draw attention to the assumption we have made in symbolising by $\phi(\Delta)$, that is a function of Δ, the probability of an error (Δ). By this symbolisation, we assert that the probability of a certain error is dependent upon the value of that error.

Of this truth we may assure ourselves without the aid of mathematical reasoning; for instance, in firing from a 9-pr. field gun, with the proper elevation, at a target 1000 yards distant, we know that the probability of an error of 300 yards in the range is improbable in a very high degree; an error of 200 yards is also improbable but in a less degree, of 100 yards still less, and so on, while we know that an error of 25 yards (at least with service guns) is not only not improbable, but highly probable.

The above symbolisation is merely [as we have yet made no hypothesis as to the form of $\phi(\Delta)$] the mathematical expression of the truth that the degree of probability as to any error is dependent in some way or another upon the amount of the error. There are, however, certain properties which, although still ignorant of the form of $\phi(\Delta)$, we yet know that function ought to possess. It is clear that $\phi(\Delta)$ must be of such a form that it will denote an equal amount of probability, when for an error in excess, *i.e.* a positive error, we substitute an error in defect, or a negative one. To return to our illustration: supposing that we obtain a range of 1000 yards as the result of practice, and suppose further, that at a certain round we are told simply that there exists an error of 25 yards, it is clearly an equal chance whether the error is in excess or defect. No person would give odds on either supposition; $\phi(\Delta)$ must then denote the same degree of probability, that is, must have the same value for $\Delta=+25$ and $\Delta=-25$.

It is also evident that $\phi(\Delta)$ must be of such a form that it will have a greater value for $\Delta=0$ than for any other value of Δ. We must, in fact, have selected such an hypothesis as to the value to be determined as will make $\phi(\Delta)$ greater for that hypothesis than for any other. It must, however, be borne in mind, that although the value selected be more probable than any other value, the probability

that it is the true value may be very small when compared with all other hypotheses. The hypothesis, for example, of the range of 1000 yards, deduced as the probable range from practice, although more probable than any other, may be, and generally is (supposing our unit to be a yard and to vary per saltum), improbable when compared with all other hypotheses.

Perhaps a clearer view of our meaning may be gained from a somewhat analogous case. If we throw in the air 24 pence, the most probable of all results is that we shall have 12 heads and 12 tails. Such an event, however, although more probable than any other result, is yet improbable when compared with all possible cases. The odds against it are about 6 to 1.

$\phi(\Delta)$ must, lastly, be such as to give only insensible magnitudes when Δ exceeds a certain limit. Suppose, for instance, that in 1000 observations 500 of the errors are less than a certain quantity r, while only one exceeds $5r$. $\phi(\Delta)$ must, then, for an error Δ near $5r$ become very small, and for errors notably greater must become infinitesimal. The knowledge of this property is derived from experience, although it might also be anticipated by reasoning.

These three properties of $\phi(\Delta)$ are thus mathematically expressed: $\phi(\Delta)$ is an even function of Δ, is a maximum for $\Delta = 0$, and sensibly vanishes when Δ exceeds a certain limit.

It would be quite out of place to enter here* upon the analytical method by which the form of the function $\phi(\Delta)$ is determined.

We must content ourselves with remarking that the expression for $\phi(\Delta)$ is found to be

$$\phi(\Delta) = \frac{h}{\sqrt{\pi}} . e^{-h^2\Delta^2} \qquad . \quad . \quad . \quad (3)$$

h being a constant, whose value is derived from the observations under discussion,—of this constant we shall hereafter speak; but supposing h for the present to be known, Equation (3) represents the law of the probability of the error Δ.

It is first obvious that $\phi(\Delta)$ possesses the properties which we have just shown that function ought to possess. We proceed to its application. Had we a perfect gun, perfect powder, etc., and could

* The mathematical reader who wishes to examine for himself the formulæ which must here be received on trust, is referred to Encke's Memoir on the Method of Least Squares, whose notation is here followed, and from which, and Professor De Morgan's works on Probabilities, this résumé is chiefly drawn. An analysis of the principles upon which the theory is founded, will be found in Mill's *System of Logic*, vol. ii. p. 58.

we fire our gun always under the same circumstances, we should of course find that the result of every shot we fired was merely a repetition of the preceding one, and any single result would be sufficient to determine the range. Calling x the range and n the observed result, we should have the range given by the equation

$$x=n$$

Instead, however, of having the result of every shot the same, we find that on an occasion when m shots were fired, we obtained the results

$$n_1, \quad n_2, \quad n_3, \quad . \; . \; . \quad n_m$$

and the question is, how are we to deduce the most probable range from the discordant equations

$$\left.\begin{array}{l} x-n_1 = 0 \\ x-n_2 = 0 \\ \quad . \; . \; . \; . \\ x-n_m = 0 \end{array}\right\} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Now it is evident that if $n_1 \; . \; . \; . \; n_m$ be all different, whatever hypothesis as to x we may make, upon that hypothesis at least $m-1$ of Equations (4) will not vanish, but will have values, which we call the errors of the respective observations; we shall have in fact

$$\left.\begin{array}{l} x-n_1 = \Delta_1 \\ x-n_2 = \Delta_2 \\ \quad . \; . \; . \; . \\ x-n_m = \Delta_m \end{array}\right\} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and the probabilities of these errors, according to the notation we have adopted, are respectively $\phi(\Delta_1)$, $\phi(\Delta_2)$, . . . $\phi(\Delta_m)$, while the probability of their concurrence is

$$\phi(\Delta_1) \times \phi(\Delta_2) \; . \; . \; . \; \times \phi(\Delta_m)\,*$$

* If p_1 be the probability of any event, p_2 that of any second event, p_3 that of any third event, p_m that of any m^{th} event, the probability of their concurrence is

$$= p_1 \times p_2 \times p_3 \; . \; . \; . \; \times p_m$$

This proposition is easily illustrated. If we throw in the air a penny, the chance of throwing heads twice in succession is $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$, or 3 to 1 against it. The chance of throwing heads three times in succession is $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$, or 7 to 1 against it, and so on.

which is by Equation (3)

$$= \frac{h^m}{\pi^{\frac{m}{2}}} \cdot e^{-h^2(\Delta_1^2+\Delta_2^2+ \,\dots\, \Delta_m^2)} \quad . \quad . \quad . \quad (6)$$

or

$$= \frac{h^m}{\pi^{\frac{m}{2}}} \cdot e^{-h^2[(x-n_1)^2+(x-n_2)^2+ \,\dots\, (x-n_m)^2]} \quad . \quad . \quad (7)$$

by virtue of Equation (5).

Now it is evident from an examination of (6) that

$$\phi(\Delta_1) \times \phi(\Delta_2) \dots \times \phi(\Delta_m)$$

is greatest when $\Delta_1^2+\Delta_2^2+ \dots \Delta_m^2$ is least,* whence follows the proposition that that hypothesis as to x is the most probable, for which hypothesis, assumed as true, the sum of the squares of the errors is the least possible, whence the name of the Method of Least Squares.

This proposition is very general, the problem above discussed being only a particular, and the most simple case; but as it is the one required for the subject under consideration, it only will now be considered.

We proceed to determine the most probable value of the constant h: from Equation (6) we have

$$\phi(\Delta_1) . \phi(\Delta_2) \dots \phi(\Delta_m) = \frac{h^m}{\pi^{\frac{m}{2}}} \cdot e^{-h^2(\Delta_1^2+\Delta_2^2 \dots +\Delta_m^2)}$$

Let us assume ϵ_2 to be such a quantity that

$$\epsilon_2^2 = \frac{\Delta_1^2+\Delta_2^2+ \,\dots\, \Delta_m^2}{m} = \frac{\Sigma(\Delta^2)}{m} \quad . \quad . \quad (8)$$

that is, we take ϵ_2 to be such that if we substituted it as the error throughout the observations, we should have the same sum of the squares of the errors as actually exists. ϵ_2 is called the mean error, and Equation (6) or (7) becomes

$$\phi(\Delta_1) . \phi(\Delta_2) \dots \phi(\Delta_m) = \frac{h^m}{\pi^{\frac{m}{2}}} \cdot e^{-mh^2\epsilon_2^2} \quad . \quad . \quad . \quad (9)$$

* This will perhaps be more easily seen if we put the right-hand member of (6) in the form

$$\frac{h^m}{\pi^{\frac{m}{2}}} \cdot \frac{1}{e^{h^2(\Delta_1^2+\Delta_2^2 \,\dots\, +\Delta_m^2)}}$$

The most probable value of h is that which makes (9) a maximum. Hence, differentiating with respect to h, and equating to zero, we have

$$1 - 2h^2\epsilon^2_2 = 0$$

$$\text{or} \qquad h = \frac{1}{\epsilon_2\sqrt{2}} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

We have above shown that that hypothesis as to x is most probable for which the sum of the squares of the errors is the least possible. Now in the simple case we are discussing, the direction to select such a result that the sum of the squares of the errors may be a minimum, is the same as if we were told to take the arithmetical mean. This may easily be verified. Suppose that four shots from a 9-pr. gun gave the results 950, 975, 1025, 1050, the mean of which ranges is 1000 yards. It will be found that the sum of the squares of the errors upon the hypothesis that 1000 yards is the true range is less than it would be upon any other hypothesis whatever.

The law of the arithmetical mean* may also be easily deduced from Equation (7) by the differential calculus. The sum of the squares of the errors is to be a minimum. Hence, from (5)

$$(x - n_1)^2 + (x - n_2)^2 \; . \; . \; . \; + (x - n_m)^2 = \text{minimum.}$$

Differentiating and equating to zero,

$$x - n_1 + x - n_2 \; . \; . \; . \; + x - n_m = 0$$

$$\text{or} \qquad x = \frac{n_1 + n_2 + \; . \; . \; . \; + n_m}{m}$$

We may from geometrical considerations obtain a graphic view of the law represented by Equation (3). If we take the values of Δ as abscissæ, and the corresponding values of $\phi(\Delta)$ as rectangular ordinates, we shall be enabled to trace the curve of probable error.

The general form of the curve of probabilities is shown in Fig. 1. In this figure the abscissæ, such as OA, OC, represent the errors, and

* It may be proper to advert here to a common misapplication of the principle of the arithmetical mean, and one which sometimes leads to serious errors. Suppose m different series of equally good observations gave m different values of the mean range $a_1, a_2 \; . \; . \; . \; a_m$. Suppose further that a_1 is the result of p_1 rounds, a_2 the result of p_2 rounds, a_m the result of p_m rounds, or as it may otherwise be expressed, suppose a_1 to have the weight p_1, a_2 the weight p_2, a_m the weight p_m—the most probable value of the range is not, as is frequently assumed,

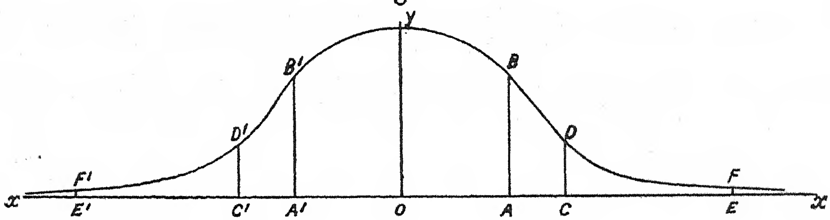
$$x = \frac{a_1 + a_2 + \; . \; . \; . \; + a_m}{m}$$

$$\text{but is} \qquad x = \frac{a_1p_1 + a_2p_2 \; . \; . \; . \; + a_mp_m}{p_1 + p_2 \; . \; . \; . \; + p_m}$$

the corresponding ordinates AB, CD the comparative probabilities of these errors.

The curve is symmetrical on each side of the axis of y, thus showing that positive and negative errors are equally probable, while the rapid decrease of the ordinate AB, as we recede from Oy, shows that large errors are not so probable as small ones, and that when we take a very large error, as OE, the corresponding ordinate, and, therefore, the probability of the occurrence of that error, becomes altogether insensible.

Fig. 1



The curve, although close to the axis of x at E, and always approaching nearer and nearer, only touches it at infinity, the axis of x being an asymptote to the curve.

As said above, the curve of probabilities is always of the nature represented in Fig. 1. The particular form it assumes is, however, dependent upon the value of the constant h. An examination of Equation (10) shows that the smaller is the mean error, that is, the more accurate are the observations, the larger is h, while Equation (3) shows that as h is large the more rapidly will $\phi(\Delta)$ or the length of the ordinate AB decrease, which is the same thing as to say that as h increases so are large errors unlikely to occur.

On account of the ratio between the increase of exactness and the increase of the magnitude of h, h has received the name of the "measure of precision."

Fig. 2 is a representation of a curve in which the value of h is large as compared with its value in Fig. 1.

If we suppose Δ to vary continuously, the probability of any particular error Δ is infinitesimal. We have pointed out that the probability of the occurrence of an error between Δ and $\Delta + d\Delta$ is $\phi(\Delta)d\Delta$, or substituting for $\phi(\Delta)$ from Equation (3)

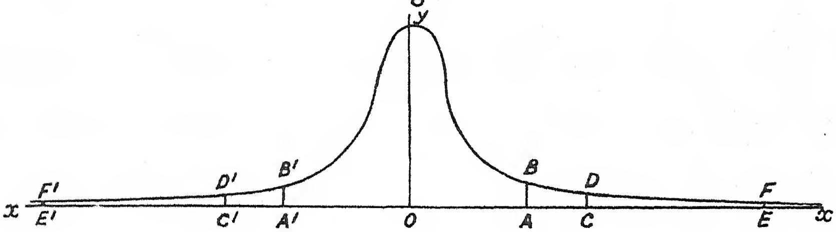
$$= \frac{h}{\sqrt{\pi}} \cdot e^{-h^2\Delta^2} \cdot d\Delta \quad . \quad . \quad . \quad . \quad . \quad (11)$$

while the probability that an error lies between $OA = a$ and $OC = c$ is given by the definite integral

$$\frac{h}{\sqrt{\pi}} \int_a^c e^{-h^2 \Delta^2} . d\Delta \quad . \quad . \quad . \quad . \quad (12)$$

This integral represents the area ACDB, Figs. 1 and 2, and it will also express the proportion of errors which should occur

Fig. 2



between $\Delta = a$ and $\Delta = c$, the whole area between the axis of x and the curve, or the whole number of errors, being unity. Putting $h\Delta = t$. Equation (12) becomes

$$= \frac{1}{\sqrt{\pi}} \int_{ah}^{ch} e^{-t^2} . dt \quad . \quad . \quad . \quad . \quad (13)$$

If we seek the probability of an error between $+a$ and $-a$, that is, if we seek the area $AA'yB'B$, Figs. 1 and 2, Equation (13) gives us

$$\text{probability} = \frac{1}{\sqrt{\pi}} \int_{-ah}^{ah} e^{-t^2} . dt$$

$$= \frac{2}{\sqrt{\pi}} \int_0^{ah} e^{-t^2} . dt \quad . \quad . \quad . \quad (14)$$

from the symmetry of the curve.

The value of this integral has been calculated and tabulated for gradually increasing values of ah, and it is evident that such a table will show by inspection the number of errors we may expect to find between any two arbitrary limits, no regard being paid to the sign of the errors.

A view of the distribution of these errors with regard to magnitude may be interesting. The number of observations is supposed

large only to show how small is the chance of the occurrence of large errors. In 10,000 errors there will probably be—

Between	$t = 0$	and	$t = 0{\cdot}5$	5205	errors
	$t = 0{\cdot}5$	,,	$t = 1{\cdot}0$	3222	,,
	$t = 1{\cdot}0$	,,	$t = 1{\cdot}5$	1234	,,
	$t = 1{\cdot}5$	,,	$t = 2{\cdot}0$	292	,,
	$t = 2{\cdot}0$	,,	$t = 2{\cdot}5$	43	,,
	$t = 2{\cdot}5$	,,	$t = 3{\cdot}0$	4	,,

and between $t=3{\cdot}0$ and $t=\infty$ there will probably not, in 10,000 observations, be a single error.

The definite integral (14) enables us also to deduce the probable error.

By probable error we understand that error, than which there are as many errors less as there are greater. The probability of such an error must be $\frac{1}{2}$, and if then we designate the probable error of a single round by r, Equation (14) becomes

$$\frac{1}{2} = \frac{2}{\sqrt{\pi}}\int_0^{hr} e^{-t^2}.\,dt \quad . \quad . \quad . \quad . \quad (15)$$

and the table of the values of this integral, of which we have spoken, shows that in this case we must have

$$hr = {\cdot}476936 = \rho, \text{ suppose} \quad . \quad . \quad . \quad (16)$$

But, by Equation (10),

$$h = \frac{1}{\epsilon_2\sqrt{2}}$$

hence
$$r = {\cdot}476936\,.\,\epsilon_2\sqrt{2} = {\cdot}674489\,.\,\epsilon_2{}^{*} \quad . \quad . \quad (17)$$

Before applying this last formula a correction must be made, the reason for which we shall endeavour to explain.

We have supposed ϵ_2 to have been determined from the true errors of observation, whereas it has been determined only from the most probable errors. Now, we have already pointed out,

* It may be useful to note, that it is an even chance that the probable error of a single datum, r, lies between

$${\cdot}6745\,.\,\epsilon_2\left(1 + \frac{{\cdot}4769}{\sqrt{m}}\right) \text{ and } {\cdot}6745\,.\,\epsilon_2\left(1 - \frac{{\cdot}4769}{\sqrt{m}}\right)$$

Also, if R be the mean range, and m be the number of rounds from which it was obtained, it is an even chance that we have not erred in our determination of R by a quantity greater than $\frac{r}{\sqrt{m}}$

that although we may select the most probable hypothesis, yet the odds are strongly in favour of our erring by a small quantity.

It will be borne in mind, that ϵ_2 was calculated so as to be a minimum, and hence the true mean error (supposing that our hypothesis is erroneous by a small quantity) will be slightly larger than the hypothetical mean error. Equation (17) would then give us a probable error rather too small, and analysis shows that the proper correction is made by substituting in Equation (8) $m-1$ for m, so that we obtain ϵ_2 as nearly as possible from the equation

$$\epsilon_2^2 = \frac{\Sigma(\Delta^2)}{m-1} \quad . \quad . \quad . \quad . \quad . \quad (18)$$

and this value of ϵ_2 must be employed in Equation (17).

We are now in a position to apply these results to practice. We shall select for illustration an actual experiment made by the Committee on Rifled Cannon to try the relative accuracy of two guns—a rifled 18-pr. of 12 cwt. and the service brass 9-pr.

The first of these guns gave, as regards range, the following data in yards:—

1023	1018	1005	1020	1005	1005	1018	1005	1026	1014
1032	1020	1025	1024	1023	1038	1032	1032	1026	1007
1002	1002	1002	1005	1018	1013	1032	1024	1005	1004
1018	1018	1025	1012	1037	1038	1032	1026	1018	1025

giving a mean range of 1019 yards.

Hence the errors of the preceding data, assuming the mean range to be the true one, are, when arranged according to magnitude and without regard to sign—

$$\left.\begin{array}{cccccccccc} 19 & 17 & 14 & 14 & 13 & 7 & 6 & 5 & 1 & 1 \\ 19 & 17 & 14 & 13 & 13 & 7 & 6 & 5 & 1 & 1 \\ 18 & 15 & 14 & 13 & 12 & 7 & 6 & 4 & 1 & 1 \\ 17 & 14 & 14 & 13 & 7 & 6 & 5 & 4 & 1 & 1 \end{array}\right\} \quad (19)$$

Taking the sum of the squares of these errors, we obtain from Equation (18) for the mean error,

$$\epsilon_2 = \sqrt{\frac{4758}{39}} = 11{\cdot}01 \text{ yards};$$

whence from Equation (17) we have the probable error,

$$r = {\cdot}6745\,\epsilon_2 = 7{\cdot}4 \text{ yards} \quad . \quad . \quad . \quad . \quad (20)$$

We pursue precisely the same course * with respect to the deflections, save that we must first reduce them all to their value at the mean range.

In the case before us the deflections at 1019 yards were, in inches—

32	right	2	left	6	right	30	right
30	„	20	right	4	left	42	„
24	„	38	„	0	„	48	„
19	„	39	„	15	right	16	„
33	„	39	„	15	„	20	„
33	„	39	„	15	„	24	„
25	„	32	„	8	„	16	„
2	left	32	„	37	„	6	left
2	right	18	„	28	„	4	„
3	„	14	„	28	„	17	right

Hence the mean point of impact is 20 inches right, and the errors, arranged according to magnitude and without regard to sign, are—

28	22	19	18	13	12	8	5	4	2
26	22	19	17	13	12	8	5	4	1
24	22	19	17	12	10	6	5	4	0
24	20	18	14	12	10	5	4	3	0

. (21)

* It is to be observed that the method here adopted is somewhat faulty. The following would be the stricter course of procedure :—

If θ be the probable angle of deflection, since θ is always very small, the angular deflection of each round is given by the equations

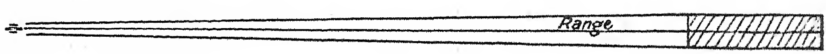
$$r_1\theta - d_1 = 0, \quad r_2\theta - d_2 = 0, \text{ etc.}$$

where r_1, r_2, etc. are the ranges, and d_1, d_2, etc. the corresponding deflections. The most probable value of θ will then be that for which

$$(r_1\theta - d_1)^2 + (r_2\theta - d_2)^2 + \text{, etc., is a minimum.}$$

It is also obvious that the probable area is not, as is here supposed, a rectangle, but is such as is shown in Fig. 3.

Fig. 3



The error, however, induced by adopting the method followed in the text is of a very small order, while the calculations are thereby very much simplified.

Equation (8) gives us for the mean error

$$\epsilon_2 = \sqrt{\frac{8425}{39}} = 14{\cdot}5 \text{ inches}$$

$$\text{and} \quad \therefore \quad r = {\cdot}6745\,\epsilon_2 = 9{\cdot}8 \text{ inches} \quad . \quad . \quad . \quad (22)$$

We have now obtained the probable error in range and in deflection. The probability of each event is $\frac{1}{2}$, and consequently the probability that a shot would fall within both the probable errors is $\frac{1}{4}$, that is, the chances are three to one against it.

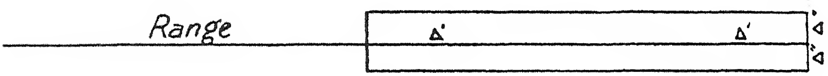
Let us now suppose that we have found an error in range Δ', within which a little more than $\frac{7}{10}$ths of the errors (${\cdot}7071$) will probably fall, and an error Δ'' in deflection, within which we may also expect ${\cdot}7071$ of the errors to fall.

The probability of a shot falling, so that its error in range shall be less than Δ', and its error in deflection less than Δ'', will be

$$= {\cdot}7071 \times {\cdot}7071 = {\cdot}5 = \tfrac{1}{2}$$

The rectangle $2\Delta' \times 2\Delta''$ (Fig. 4), then, is a rectangle such

Fig. 4



that there is an even chance of any one shot falling within it, and this area, as before mentioned, I have named the probable rectangle.

Now, the definite integral (14) enables us to find Δ' and Δ''. For that integral has been tabulated according to an argument in which the probable error is assumed to be unity. For the argument $\frac{\Delta}{r}$ the table gives the value of

$$\frac{2}{\sqrt{\pi}}\int_0^{\rho\frac{\Delta}{r}} . \, e^{-t^2} . \, dt \quad . \quad . \quad . \quad . \quad (23)$$

that is, it shows how many errors may be expected to be less than a given error, provided the ratio of the given error to the probable error be known.

Conversely, the value of (23), or the number of errors which should fall within a certain unknown limit, Δ being known, the table will give the proportion which Δ bears to the probable error.

In the case before us, we have

$$\frac{2}{\sqrt{\pi}}\int_0^{\rho\frac{\Delta}{r}} e^{-t^2}.dt = \cdot 7071 \quad . \quad . \quad . \quad . \quad (24)$$

and the table shows that, in this case, we have

$$\frac{\Delta}{r} = 1\cdot 56 \text{ or } \Delta = 1\cdot 56r \quad . \quad . \quad . \quad (25)$$

Hence, from Equations (20) and (22) in the case we are discussing, we have

$$\Delta' = 11\cdot 54 \text{ yards and } \Delta'' = 15\cdot 29 \text{ inches,}$$

and the probable rectangle laid down as shown in Fig. 4, is 23·1 yards long by 30·6 inches broad.

The field gun which was fired for comparison with the rifled gun, practice from which has been just discussed, gave the following ranges:—

1038	825	1096	1078	977	1021	1014	849	1034	1001
1038	950	1033	1007	1030	910	875	953	942	1013
1053	1006	902	900	1090	1138	975	975	960	940
1008	1080	965	925	1061	932	994	979	910	912

Giving a mean range of 984·75 yards or 985 yards. Hence, the errors arranged as before, according to magnitude, and without regard to sign, are—

160	110	85	75	53	43	36	28	21	10	
153	105	83	73	49	43	35	25	20	9	. (26)
136	95	76	68	48	43	32	23	16	8	
111	93	75	60	45	41	29	22	10	6	

and taking the sum of the squares of these errors, we have, from Equation (18),

$$\epsilon_2 = \sqrt{\frac{190372}{39}} = 69\cdot 9 \text{ yards} \quad . \quad . \quad . \quad (27)$$

$$\text{whence} \quad r = \cdot 6745\epsilon_2 = 47\cdot 2 \text{ yards} \quad . \quad . \quad . \quad (28)$$

Again, the deflections in feet, at the mean range, were—

24 right	42 right	6 right	18 left
12 ,,	3 ,,	6 ,,	0 ,,
22 ,,	12 ,,	9 ,,	0 ,,
24 ,,	12 ,,	9 ,,	0 ,,
12 ,,	6 ,,	9 left	0 ,,
33 ,,	9 ,,	9 ,,	0 ,,
18 ,,	9 ,,	3 ,,	0 ,,
21 ,,	24 ,,	3 ,,	0 ,,
9 ,,	6 ,,	18 ,,	0 ,,
18 ,,	6 ,,	12 ,,	0 ,,

hence the errors are—

$$\left.\begin{array}{cccccccccc} 35 & 20 & 17 & 11 & 7 & 7 & 7 & 5 & 2 & 1 \\ 26 & 19 & 16 & 11 & 7 & 7 & 5 & 4 & 2 & 1 \\ 25 & 17 & 16 & 10 & 7 & 7 & 5 & 2 & 2 & 1 \\ 25 & 17 & 14 & 10 & 7 & 7 & 5 & 2 & 1 & 1 \end{array}\right\} \quad . \quad . \quad (29)$$

and summing the squares of these errors, we have

$$\epsilon_2 = \sqrt{\frac{6711}{39}} = 13{\cdot}1 \text{ feet}$$

$$r = {\cdot}6745\,\epsilon_2 = 8{\cdot}8 \text{ feet} \quad . \quad . \quad . \quad . \quad (30)$$

and multiplying the values of r, given in Equations (28) and (30), by 3·12, we obtain for the probable rectangle in this case a space of 147·2 yards in length by 9·1 yards in breadth.

Figs. 5 and 6 (see Plate I., p. 22) show the comparative areas of the probable rectangles of these guns at the given ranges.

For the sake of clearness, the various steps to be taken in order to ascertain the probable rectangle by the foregoing method are here recapitulated.

First, as regards range—

Find the mean range, and assuming it to be the true range, find the errors of each round.

Square these errors, and calculate the mean error from the formula

$$\epsilon_2 = \sqrt{\frac{\Sigma(\Delta^2)}{m-1}} \quad . \quad . \quad . \quad . \quad . \quad (31)$$

where $\Sigma(\Delta^2)$ = sum of the squares of the errors and m = number of rounds fired.

Calculate the probable error from the formula

$$r = {\cdot}6745\,\epsilon_2 \quad . \quad . \quad . \quad . \quad . \quad (32)$$

Second, as regards deflection—

Reduce all the deflections to their value at the mean range. Find the mean point of impact, and thence the error in deflection of each round. Square the errors, and the mean error will be given by Equation (31), the probable error by Equation (32).

Lastly, multiply the probable error both in range and deflection by 3·12. We shall then have the dimensions of the probable rectangle.*

* It is probable that we do not err in our determination of the probable rectangular area by a quantity greater than $\sqrt{\alpha^2\beta'^2 + \alpha'^2\beta^2}$ where α, β are the sides of the probable rectangle, and

$$\alpha' = \frac{{\cdot}477\,.\,\alpha}{\sqrt{m}}, \quad \beta' = \frac{{\cdot}477\,.\,\beta}{\sqrt{m}}$$

m being the number of rounds fired.

The foregoing method of determining the probable error from the sum of the squares of the errors, gives us that probable error with greater certainty than can be attained by any other method. The operation of squaring the errors, however, is laborious, especially if the number of observations be large; and the method is in truth too great a refinement for ordinary artillery practice.

We proceed to indicate a method by which the value of r may be obtained from a knowledge of the errors merely, and which, from its simplicity, and from its indicating the probable error with quite sufficient exactness, is well adapted for general application to artillery practice. Symbolising by ϵ_1 the arithmetical mean of all the errors, we must have in this case*

$$\epsilon_1 = \frac{\Sigma.\Delta}{m-1} \quad . \quad . \quad . \quad . \quad . \quad (33)$$

where $\Sigma\Delta =$ sum of the errors, without regard to sign; r is determined by the equation

$$r = \cdot 8453\,\epsilon_1 \quad . \quad . \quad . \quad . \quad (34)$$

We have mentioned that when r is determined from ϵ_2, it is an even chance that r lies between

$$\cdot 6745\,\epsilon_2\left(1 \pm \frac{\cdot 4769}{\sqrt{m}}\right) \quad . \quad . \quad . \quad . \quad (35)$$

In this case, it is an even chance that the value of r lies between

$$\cdot 8453\,\epsilon_1\left(1 \pm \frac{\cdot 5095}{\sqrt{m}}\right) \quad . \quad . \quad . \quad . \quad (36)$$

and the numerical part of the limiting values shows that we obtain r within the narrowest limits when we determine it from ϵ_2.

Let us now apply this method for the purpose of comparison to the cases we have already examined. In the first of these cases we find from (19) that, with reference to range,

$$\Sigma(\Delta) = 366$$

$$\therefore \quad \epsilon_1 = \frac{366}{39} = 9\cdot 38 \text{ yards}$$

$$\text{and} \quad r = 7\cdot 9 \text{ yards} \quad . \quad . \quad . \quad . \quad (37)$$

* *See* Encke, on the Method of Least Squares.

Again, with reference to deflection, from (21)

$$\Sigma(\Delta) = 487$$

$$\therefore \quad \epsilon_1 = \frac{487}{39} = 12{\cdot}4 \text{ inches}$$

$$\text{and} \quad r = {\cdot}845\,\epsilon_1 = 10{\cdot}4 \text{ inches} \quad . \quad . \quad (38)$$

and these results, it will be perceived, differ but slightly from those obtained in (20) and (22).

In the second case, from (26) we have

$$\Sigma(\Delta) = 2253$$

$$\therefore \quad \epsilon_1 = \frac{2253}{39} = 57{\cdot}7 \text{ yards;}$$

$$\therefore \quad r = 48{\cdot}6 \text{ yards} \quad . \quad . \quad . \quad . \quad (39)$$

Also, from (29) we have

$$\epsilon_1 = \frac{391}{39} = 10 \text{ feet}$$

$$\text{and} \quad r = 8{\cdot}4 \text{ feet} \quad . \quad . \quad . \quad . \quad . \quad (40)$$

Results again differing by small quantities only from those obtained in (28) and (30).

Hence, to obtain the probable rectangle by this method, find the mean range, and thence the error of each round; calculate the mean error from the equation

$$\epsilon_1 = \frac{\Sigma(\Delta)}{m-1} \quad . \quad . \quad . \quad . \quad . \quad (41)$$

where $\Sigma(\Delta)$=sum of the errors without regard to sign, and m= number of rounds fired.

Calculate the probable error from the equation

$$r = {\cdot}8453\,\epsilon_1 \quad . \quad . \quad . \quad . \quad . \quad (42)$$

Find the mean point of impact, and thence the error in deflection of each round. Compute the mean and probable errors from Equations (41) and (42).

Finally, multiply the probable error, both in range and deflection, by 3·12, to give the lengths of the sides of the probable rectangle.

We shall now apply this method to solve a question which has lately been the subject of extended practice under the direction of Captain Haultain, viz., to find the advantage, if any, in point of accuracy, gained by using with the service 9-pr. a charge of 3 lbs. instead of that at present in use, viz., $2\frac{1}{2}$ lbs.

B

The $2\frac{1}{2}$ lbs. charge gave the following ranges with 2° elevation:—

798	844	876	893	907	921	943	963	1016	1050
798	845	880	897	908	927	944	964	1017	1050
811	850	880	897	912	930	947	967	1018	1066
818	850	881	898	913	930	947	973	1022	1082
819	850	883	899	915	931	950	974	1024	1082
821	853	884	900	916	931	950	976	1029	1089
822	857	885	901	916	932	950	983	1030	1123
825	867	885	904	916	932	952	1002	1042	1132
837	868	889	905	920	934	954	1010	1049	1139
842	869	891	905	920	935	962	1015	1050	1177

giving a mean range of 936 yards. Four of these rounds we shall discard for the following reason:—In a considerable number of observations, such as is here discussed, we have a right to expect that the greatest errors in excess shall not differ very greatly from the greatest errors in defect. In this case, however, the maximum positive error exceeds the maximum negative by more than a 100 yards, a very improbable result; and as every officer who has had charge of a range party knows how liable, even with the greatest care, is the second graze to be mistaken for the first, we think we may here safely take the liberty of expunging the four rounds which give positive errors so much exceeding the maximum of negative errors. This liberty should, however, be most sparingly exercised, and never without adequate cause.

We have now as a mean range 927 yards, and the following system of errors, arranged as before, according to magnitude and without regard to sign:—

162	116	95	77	47	37	26	19	7	
156	115	91	77	47	36	25	17	7	
155	107	90	75	47	36	23	16	6	
139	108	90	74	46	35	23	15	5	
129	106	89	70	46	34	23	14	5	
129	105	88	60	44	30	23	12	4	(43)
123	103	85	59	43	30	22	11	4	
123	102	83	58	42	29	22	11	3	
123	102	83	56	42	28	20	11	3	
122	97	82	51	40	27	20	8	0	
		77	49	38	27	20	7		

$$\therefore \qquad \epsilon_1 = \frac{5240}{95} = 55{\cdot}1 \text{ yards}$$

$$\text{and} \qquad r = {\cdot}8453\,\epsilon_1 = 46{\cdot}5 \text{ yards} \qquad . \quad . \quad (44)$$

The deflections corresponding to the above ranges were, in feet—

4th Jan.	11 left	9 left		19 left	12 right		17 right	14 right	14 right		1 left
	20 ,,	9 ,,		40 ,,	26 ,,		7 ,,	20 ,,	39 ,,		9 ,,
	5 ,,	0 ,,		14 ,,	31 ,,		63 ,,	17 ,,	5 ,,		6 ,,
	5 ,,	12 ,,		1 right	7 ,,			31 ,,	22 ,,		6 ,,
	25 ,,	1 ,,		2 ,,	16 ,,	21st Jan.	30 right	63 ,,	17 ,,		
	9 ,,	27 ,,		2 ,,	20 ,,		13 ,,	16 ,,	37 ,,	25th Jan.	2 left
	2·5 right	26 ,,		8 ,,	8 ,,		15 ,,	23 ,,	6 ,,		29 ,,
	7·5 ,,	3 ,,			23 ,,		19 ,,	27 ,,	8 ,,		23 ,,
		8 ,,	11th Jan.	19 left	47 ,,		28 ,,	47 ,,	35 ,,		15 ,,
7th Jan.	2 left	8 ,,		4 ,,	3 ,,		38 ,,	17 ,,	8 ,,		14 ,,
	31 ,,	1 ,,		7 right	56 ,,		15 ,,	15 ,,	20 ,,		17 ,,
	54 ,,	23 ,,		20 ,,	13 ,,		16 ,,	37 ,,	10 left		4 right
	22 ,,			57 ,,			32 ,,				6 ,,

and these deflections (the effects of wind being eliminated by calculating the errors for each day separately) give the system of errors—

44	25	17	13·5	11	6·5	4	2·5
42·5	24·5	16	13	10·5	6	4	2
41·5	20·5	15·5	13	10·5	6	3·5	2
39·5	20	15	12·5	10·5	5·5	3·5	2
36·5	20	14·5	12·5	9·5	5	3·5	1·5
35·5	19	14·5	12	9·5	5	3	1
29	18·5	14·5	12	9·5	4·5	3	1
28	18	14	12	9	4·5	3	1
28	18	13·5	11·5	9	4·5	3	0·5
27·5	18	13·5	11·5	8·5	4	3	0·5
26·5	17·5	13·5	11	8	4	3	0·5
25	17	13·5	11	7·5	4	3	0·0

. (45)

and from these errors,

$$\epsilon_1 = \frac{1186{\cdot}5}{95} = 12{\cdot}5 \text{ feet}$$

$$\text{and} \qquad r = {\cdot}8453\,\epsilon_1 = 10{\cdot}5 \text{ feet} \qquad . \quad . \quad . \quad (46)$$

and the probable rectangle is 145·1 yards in length by 10·9 yards in breadth.

The 3 lbs. charge from the same guns gave the following ranges:—

816	897	927	947	967	990	1002	1018	1033
820	900	927	950	968	991	1003	1019	1043
826	904	928	950	972	991	1003	1021	1072
839	908	933	951	975	991	1006	1022	1073
863	908	933	951	978	991	1007	1022	1076
868	910	933	952	979	992	1009	1025	1077
873	910	935	955	979	994	1010	1026	1080
877	911	936	960	980	999	1011	1026	1082
882	915	938	960	981	1001	1012	1029	1109
883	919	943	964	987	1001	1012	1030	1112
895	926	947	964	990	1002	1016	1032	1130

One round was discarded from this series for the reason mentioned in the discussion of the preceding case. The remaining rounds gave a mean of 972 yards, and the following system of errors:—

158	104	71	57	45	37	29	20	9	
156	104	68	54	45	37	29	19	8	
152	101	64	54	44	36	27	19	8	
146	100	64	53	44	35	25	19	8	
140	99	62	53	40	34	25	19	7	
137	95	62	50	40	34	22	18	7	(47)
133	90	61	50	39	31	22	18	6	
110	89	61	49	39	31	22	17	5	
109	77	60	47	39	30	21	15	4	
108	75	58	46	39	30	21	12	3	
105	72	57	46	38	29	20	12	0	

$$\text{Hence} \qquad \epsilon_1 = \frac{5041}{98} = 51{\cdot}4 \text{ yards}$$

$$\text{and} \qquad r = {\cdot}8453\,\epsilon_1 = 43{\cdot}5 \text{ yards} \quad . \quad . \quad . \quad (48)$$

The errors in deflection, the wind being eliminated as in the former example, were, in fact—

34	21	15·5	13	10	7	5	3·5	1	
30	21	15	13	10	6·5	5	3	1	
27	20	15	12	9	6	5	3	1	
24	19	14	12	9	6	5	3	1	
24	19	14	12	9	6	5	3	1	
23	19	14	11·5	9	6	5	2	·5	(49)
23	19	14	11	8	6	4	2	·5	
22	18	14	11	8	6	4	2	·5	
22	17	14	11	7	6	4	2	0	
21	16	13	11	7	6	4	1	0	
21	16	13	11	7	5	4	1	0	

$$\text{and} \qquad \epsilon_1 = \frac{1008{\cdot}8}{98} = 10{\cdot}3 \text{ feet;}$$

$$\text{whence} \qquad r = {\cdot}8453\,\epsilon_1 = 8{\cdot}7 \text{ feet} \quad . \quad . \quad . \quad (50)$$

and hence the probable rectangle is 135·7 yards in length by 9 in breadth.

These comparative areas are exhibited in Figs. 7 and 8* (Plate I.,

* It will be seen by comparing Equations (4) and (40) that the probable deflection deduced from the $2\frac{1}{2}$ lbs. charge in Captain Haultain's practice is somewhat larger than that obtained by the Committee on Rifled Cannon, with a similar charge and at a similar range. This is doubtless attributable to Captain Haultain's practice having been chiefly carried on during a wind variable and across the range.

p. 22), and it follows that the 3 lbs. charge gives results slightly but decidedly more accurate than those of the $2\frac{1}{2}$ lbs. charge.*

This advantage in point of accuracy does not, however, appear to increase in a marked manner at higher angles.

We have partially discussed the practice made with the $2\frac{1}{2}$ lbs. and 3 lbs. charges at 4° of elevation.

To avoid a tedious repetition of numerical examples, we merely give diagrams of the probable rectangles, with their dimensions, in Figs. 9 and 10 † (Plate I., p. 22), drawing attention to the singular decrease in accuracy caused by an increase in the range of about 400 yards, the probable deflection being in fact more than doubled, while the range is not increased by 50 per cent.; and it would follow that a limit is soon reached beyond which it is mere waste of ammunition to fire at an object even of considerable size.

There is yet another way of attaining, when the observations are numerous, to an approximate knowledge of the probable error. We have defined the probable error to be that error than which there are as many errors less as there are errors greater; hence, if the number of observations be odd, the centre error (supposing the errors to be arranged according to magnitude), and if the number be even, the mean of the two centre errors, ought to give an approximation to the probable error. The probable errors deduced in this way from (43), (45), (47), and (49), are 44 yards, 11 feet, 40 yards, and 9 feet—results not differing very greatly from those given in (44), (46), (48), and (50).

It now only remains to say a few words relative to the employment of the methods pointed out.

We have remarked on the rapid increase of error in the 9-pr. field gun, but we may put the more general question, "What is the relative accuracy of the various guns and projectiles now in the service, and what are the limits of their effective ranges?" A series of experiments for the purpose would easily enable us to answer this question, and it is clear that an accurate knowledge of the powers of the guns would not only help to a right decision with regard to the

* It may be mentioned as a point of interest, that Captain Haultain's practice above discussed was carried on on five different days. The probable rectangle was calculated separately from the result of each day's practice as well as from the combination of all the days. The differences between these probable rectangles were very trifling, thus showing in a remarkable manner how regular in its irregularities was the practice obtained from these 9-pr. guns.

† It is to be observed in comparing the relative errors of the $2\frac{1}{2}$ lbs. and 3 lbs. charges, that the errors of the 3 lbs. charge belong to a range somewhat greater than that of the $2\frac{1}{2}$ lbs. charge.

most suitable * for any particular service, but might be a valuable guide in reducing our list of ordnance.

We should also, from a series of suitable experiments, be enabled, as has been suggested by Captain Lyons, to determine approximately the errors which are due to some specific causes, such as eccentricity of shot, etc., and also determine the increase of accuracy due to a decreased windage.

There is perhaps no branch of mathematics from which more information of importance to practical artillerymen can be gained than from the Theory of Probabilities. In the preceding pages, an attempt has been made to develop one of its applications, and although it has been impossible to enter fully into the subject within the limits of such a paper as the present, we yet trust that the utility of applying its methods to the examination of artillery practice has been sufficiently exhibited.

* To take an instance which has been the subject of considerable discussion, we would be enabled at once to assign the advantages in point of accuracy possessed by the 9-pr. over the 6-pr. at various ranges.

PLATE. I.

From Experiments of Committee on Rifled Cannon.

FIG. 5.

Probable rectangle, Rifled 18 P.R Mean Range 1018 yards.

23·1 yards.

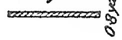
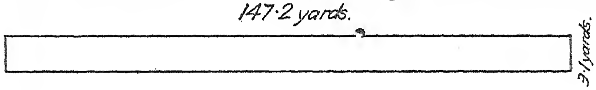


FIG. 6.

Probable rectangle, Service Brass 9 P.R, Charge 2½ Lbs, Mean Range 985 yards.

147·2 yards.



From Captain Haultain's Practice.

FIG. 7.

Probable rectangle, Service Brass 9 P.R, Charge 2½ Lbs, Mean Range 927 yards.

145·1 yards.

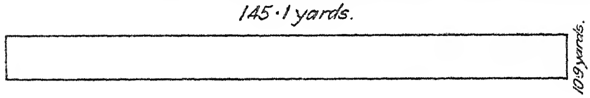


FIG. 8.

Probable rectangle, Service Brass 9 P.R, Charge 3 Lbs, Mean Range 972 yards.

135·7 yards.

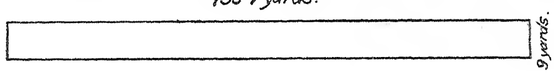


FIG. 9.

Probable rectangle, Brass 9 P.R, Charge 2½ Lbs, Mean Range 1332 yards.

206 yards.

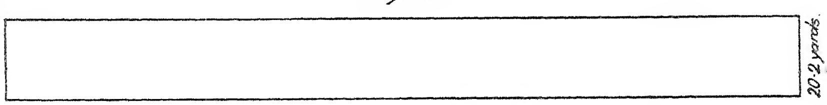
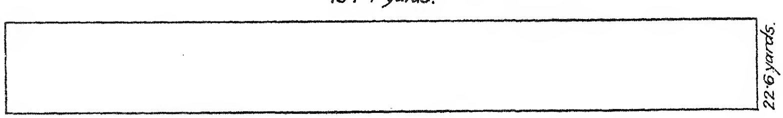


FIG. 10.

Probable rectangle, Brass 9 P.R, 3 Lbs Charge, Mean Range 1409 yards.

194·7 yards.



[To face p. 22.

II.

REPORT ON EXPERIMENTS WITH NAVEZ'S ELECTRO-BALLISTIC APPARATUS.

(*Royal Artillery Institution Papers*, 1863.)

1. In forwarding to the Ordnance Select Committee the results of the experiments in initial velocity, which I have had the honour of carrying on under their direction, I have to make the following remarks:—

2. The instrument employed in these investigations was the electro-ballistic apparatus of Major Navez,* and it may not be out of place here to recapitulate the leading points of its construction.

The apparatus itself is merely an arrangement for measuring, with extreme accuracy, a certain very small interval of time. Two screens, the nearer one a short space from the muzzle of the gun, are placed at an accurately measured distance apart, and it is the object of the instrument to ascertain the time which the projectile takes to pass over this measured space.

3. The apparatus consists of three parts, the pendulum, etc., the conjunctor, and the disjunctor. The principal part is the pendulum and graduated arc. The pendulum, before an observation, is held suspended by an electro-magnet, the current magnetising which, passes through the first screen. To the pendulum is attached, by means of the pressure of a spring, an arm with a vernier. The pressure of this spring is so regulated that the arm vibrates freely with the pendulum, but at the same time it offers but little resistance to the action of a powerful horse-shoe electro-magnet, which, when the circuit magnetising it is complete, clamps the vernier arm with great firmness.

4. The current which passes through the second screen holds, by

* Belgian Artillery.

means of an electro-magnet, a weight suspended over a spring, a point from which is kept just over a cup of mercury. When this weight is permitted to fall, it presses the point into the cup of mercury, and completes the circuit, magnetising the horse-shoe magnet, which clamps the vernier needle. This part of the apparatus is termed the conjunctor. The action of the instrument is very simple, and readily understood. When the projectile cuts the wires in the first screen, the magnet which holds the bob of the pendulum in its initial position is demagnetised, and the pendulum commences an oscillation. When the wires in the second screen are cut, the weight of the conjunctor drops, completes the circuit, clamping the vernier, and the arc through which the pendulum has moved is a datum from which may be computed the corresponding time.

5. An important part of the apparatus (the disjunctor) remains yet to be mentioned. It will be obvious that the arc, which we have just supposed to be measured, corresponds to the time which the projectile takes to pass over the distance between the screens, plus the time which the weight of the conjunctor takes to fall from its initial position to the cup of mercury. Now, to obtain the former, the latter of these times has to be subtracted from the reading of the instrument, and the disjunctor enables us to do this by permitting us to break both currents (those through the first and second screens) simultaneously. The mode of procedure is then as follows:—The instrument being arranged, the two currents are simultaneously broken by means of the disjunctor, and the reading of the needle is recorded. The instrument is again adjusted, the projectile fired (the velocity of which it is desired to determine), and the reading of the needle again noted; the former arc is subtracted from the latter, and the corresponding time computed. It will be observed that, by the use of the conjunctor, any constant source of error (such, for example, as the error due to the time required to clamp the vernier needle) is eliminated, as the same error will occur both in the disjunctor and the projectile reading, and by subtraction will disappear.

The disjunctor also enables us to ascertain the degree of regularity with which the instrument is working, as the accidental variations of the reading corresponding to the time 0 are, of course, the same as the variations which would occur in the reading corresponding to any other time. Major Navez lays down, as a rule, that observations should not be proceeded with when in a series of ten or twelve disjunctor readings there is between two successive readings a difference greater than $0^\circ{\cdot}25$.

6. It is of some importance to be enabled to put an exact estimate on the degree of reliance to be placed on the results of Major Navez's beautiful instrument; and, to do this, let us observe that the arc from which the required time is computed is the difference between two arcs, in our estimation of each of which we are liable to a small error. We have in fact the value of one arc Φ given by the equation

$$\Phi = \phi - \phi' . \qquad . \quad . \quad . \quad . \quad . \quad (1)$$

where ϕ and ϕ' are each subject to probable errors (let us suppose) r and r'; the probable error of Φ is then $\sqrt{r^2 + r'^2}$. If, after the satisfactory working of the instrument has been ascertained and the probable error determined, we take a single reading with the disjunctor, and then with the projectile, r and r' are equal, and the probable error of the observation is $r\sqrt{2}$. We have it, however, in our power, if it be thought necessary, to reduce even this error, for if the disjunctor reading be taken, the mean of, say five observations, we have $h' = \frac{r}{\sqrt{5}}$, and the probable error of Φ is $r\sqrt{\frac{6}{5}}$, which differs but slightly from r. An example will show how very trifling this error generally is. With an Armstrong 12-pr. shell, whose velocity is determined to be 1181 feet per second, the value of r is found to be $0^\circ{\cdot}06$, and the disjunctor reading being the mean of five observations, the probable error of Φ is $0^\circ{\cdot}07$.

Hence the disjunctor reading being $42^\circ{\cdot}85$, and the projectile reading $107^\circ{\cdot}40$, it follows that it is probable that in our determination of 1181·2 feet as the velocity at a point midway between the screens, we do not make an error exceeding 1·4 feet; that is to say, it is an even chance that the true velocity of the single observation lies between 1179·8 feet and 1182·6 feet. As the round from which the above example is selected is one of a series of ten, the probable error in our determination of the mean velocity between the screens will be less than one-third of that just given, or the mean velocity may be assumed, as far as instrumental errors are concerned, to be practically correct.

7. The experience which I have had with Major Navez's instruments enables me to say, that if ordinary care be taken in their use, and the instructions carefully followed, the instruments are so nearly perfect as to leave little to be desired, while the ease with which they can be manipulated and the innumerable important problems which can be readily solved by their means, render them an invaluable, an almost indispensable, adjunct to every school of instruction.

8. Two instruments, Nos. 24 and 32, were used in these experiments. The times of vibrations of the pendulums were carefully determined by means of a stop-watch, and the rate of the watch was ascertained by comparison with an astronomical clock. The observations made for this purpose are given in Appendices * Nos. I. and II., and from them it appears that the time of a small oscillation in instrument No. 24 is 0·3320 seconds, while in No. 32 it is 0·3337 seconds.

9. In Appendices* III. and IV. are given corrected tables, showing the relations between the arcs passed through and the corresponding durations for T=0·3320 seconds, and for T=0·3337 seconds.

10. The experiments referred to in this report have regard chiefly to initial velocity alone; and for the small distance concerned, the law of resistance adopted may be thought of small practical importance, especially as before the experiments now carried on are concluded, the Committee will doubtless be in a position to say whether this law is better expressed by a function of the form $v^2 + av^3$, as proposed by General Piobert, or by one of the form $v^2 + \beta v^4$, as proposed by the Count de St Robert and Colonel Mayevski. In the present instance, both the law of resistance and the values of the coefficients given by General Didion in his invaluable work have been followed, although it may, perhaps, be inferred from a passage in the recent edition of the *Traité de Balistique,* that late experiments with the electro-ballistic apparatus do not give results in quite so close an accordance with theory as might have been expected.

11. In the first edition of General Didion's work, published in 1848, a term was introduced into the expression of the resistance of the air dependent upon the diameter of the projectile, and this form of the expression has been generally used upon the Continent; but a recalculation of the data upon which this result was founded has led General Didion to conclude that the coefficient is independent of the calibre, and that the resistance is represented with sufficient accuracy by the equation

$$\rho = \cdot 027\pi R^2 v^2 . \frac{\delta}{\delta_1}\left\{1 + \frac{v}{435}\right\} \quad . \quad . \quad . \quad (2)$$

where R=radius, v=velocity, δ=density of the air at time of

* These Appendices, having reference only to the use of the instruments now superseded, are omitted.

observation, and δ_1 = standard density of air; the metre and the kilogramme are taken as units.

In this formula the density of the air is denoted by referring its weight to a standard of comparison, which is assumed as the weight of a cubic metre of air at a temperature of 15° Cent., semi-saturated with vapour, and under a barometric pressure of 760 mm.

Now, if in Equation (2) the English foot and pound be taken as units, the value of the numerical coefficients will be altered, and the equation becomes

$$\rho = \cdot 0005137\pi R^2 v^2 . \frac{\delta}{\delta_1}\left\{1 + \frac{v}{1426\cdot 4}\right\}$$

In the ordinary determinations of initial velocity it is hardly necessary to take the variations of the density of the air into account, and it only remains so to alter the coefficient ·0005137 that the error arising from neglecting this variation may be as small as possible.

12. According to Regnault, the weight of a cubic foot of dry air at a temperature of 32° Fahr., and under a barometric pressure of 30 inches, is = 566·56 grains; and according to the same author, the coefficient of the expansion of the air for an increase in temperature of 1° Fahr. is = ·002036. Hence if δ be the weight in grains of a cubic foot of dry air at any temperature t, and pressure Π,

$$\delta = \frac{\Pi}{30} . \frac{566\cdot 56}{1 + \cdot 002036\,(t^\circ - 32^\circ)}$$

but (see Miller's *Hydrostatics*, p. 28)—

$$\frac{\text{Weight of moist air at any temperature and pressure}}{\text{Weight of dry air at same temperature and pressure}} = 1 - 0\cdot 378\frac{T}{\Pi}$$

where T = tension of the aqueous vapour. Hence the density of the air under any circumstances will be found from the following equation:—

$$\delta = \frac{\Pi}{30} . \frac{\left(1 - 0\cdot 378\,\frac{T}{\Pi}\right) 566\cdot 56}{1 + \cdot 002036\,(t^\circ - 32^\circ)} \quad . \quad . \quad . \quad (3)$$

And if we assume as the English standard of comparison the weight of a cubic foot of air at a temperature of 60°, under a barometric

pressure of 30 inches, and if we further assume the humidity = 0·5, from (3) we find $\delta = 534{\cdot}3$ grains, and Equation (2) becomes

$$\rho = {\cdot}0005213\pi R^2 v^2 \left(1 + \frac{v}{1426{\cdot}4}\right)\frac{\delta}{534{\cdot}3} \quad . \quad . \quad (4)$$

and under ordinary circumstances the fraction $\frac{\delta}{534{\cdot}3}$ may be taken as equal to unity.

13. The above formula (4) applies to spherical projectiles; in the case of the Armstrong projectiles, the resistance of the air is represented by

$$\rho = {\cdot}0003475\pi R^2 v^2 \left(1 + \frac{v}{1426{\cdot}4}\right)\frac{\delta}{534{\cdot}3} \quad . \quad . \quad (5)$$

The velocity v at a point midway between the screens having been determined by observation, the initial velocity v is deduced from it by the equation

$$1 + \frac{r}{v} = \left(1 + \frac{r}{v}\right)e^{\frac{x}{2c}} \quad . \quad . \quad . \quad . \quad (6)$$

where $r = 1426{\cdot}4$, x = distance, on the axis of the gun produced, of the point corresponding to v, $c = \frac{w}{2ng}$, w being the weight of the projectile in lbs., g the acceleration of gravity, and n, in the case of spherical projectiles, $= {\cdot}0005213\pi R^2$; in the case of Armstrong projectiles, $= {\cdot}0003475\pi R^2$.

14. Discussion of the results. The experiments made relate solely to the determination of the initial velocity of service projectiles fired from service guns with service charges. The detailed results of the practice furnished *in extenso* give every particular with regard to it, and the table on next page gives an abstract of the general results.

It will be observed that the values of the "Measure of precision" for each of the series of which the result is here given, is placed in the above table in a separate column. The value of this constant denotes the comparative regularity of the initial velocity.

As might perhaps be expected, from the absence of windage, the 12-pr. Armstrong has shown the greatest regularity, and I have therefore assumed the measure of precision for this gun as unity.

An inspection of the values of the "Measure of precision" will show how great is the amount of irregularity which exists in the

TABLE 1.—*Abstract of the results of experiments to ascertain the initial velocity of service projectiles fired from service guns with service charges.*

Nature of Ordnance.	No. of rounds.	Charge.		Projectile.			Velocity at 30 yards.	Measure of precision.	Initial velocity.	Initial energy.
		Weight.	Nature of powder.	Nature.	Weight.	Diameter.				
		Lb. oz.			Lb. oz.		F. S.		F. S.	F. T.
10-in. gun (87 cwt.)	10	12 0	L. G., W. A.	Hol. shot	88 5	9·838	1270·4	0·490	1292·3	1022·2
,, ,,	5	8 0	L. G., Hall & Sons	Mar. shell	117 0	9·838	930·1	0·175	940·6	717·2
68-pr. (95 cwt.)	12	16 0	L. G., W. A.	Shot	66 4	7·915	1553·1	0·703	1579·0	1145·3
,, ,,	7	16 0	L. G., Hall & Sons	Nav. shell	51 8	7·913	1769·4	0·237	1809·9	1169·5
,, ,,	9	16 0	,, ,,	Com. shell	49 14	7·857	1750·3	0·348	1790·7	1108·7
,, ,,	5	10 0	,, ,,	Mar. shell	60 0	7·848	1287·6	0·131	1308·5	712·2
8-in. gun (65 cwt.)	5	10 0	,, ,,	Hol. shot	46 0	7·84	1455·0	0·504	1487·9	706·1
,, ,,	5	10 0	,, ,,	Com. shell	49 14	7·856	1434·6	0·573	1464·4	741·6
,, ,,	5	10 0	,, ,,	Nav. shell	51 8	7·92	1475·8	0·306	1506·4	810·1
32-pr. (58 cwt.)	10	10 0	L. G., W. A.	Shot	31 6	6·174	1653·7	0·425	1690·0	621·3
,, ,,	11	8 0	,, ,,	,,	31 6	6·176	1584·7	0·640	1618·7	570·1
,, ,,	11	6 0	,, ,,	,,	31 6	6·175	1418·8	0·504	1447·5	455·9
24-pr. (50 cwt.)	11	8 0	,, ,,	,,	23 8	5·602	1679·5	0·323	1720·5	482·3
18-pr. (38 cwt.)	12	6 0	,, ,,	,,	17 11	5·093	1646·8	0·148	1690·6	350·5
12-pr. (18 cwt.)	10	4 0	L. G.	,,	12 10½	4·52	1718·6	0·384	1769·8	274·9
9-pr. (13 cwt.)	10	2 8	,,	,,	9 5¾	4·10	1563·9	0·406	1613·7	168·9
6-pr. (6 cwt.)	10	1 8	,,	,,	6 3¾	3·58	1435·3	0·418	1484·5	95·2
12-pr. howitzer (6½ cwt.)	10	1 4	,,	Com. shell	8 12	4·454	1124·2	0·270	1163·4	82·1
24-pr. howitzer (12 cwt.)	10	2 8	,,	,,	16 11½	5·595	1218·0	0·368	1252·7	182·0
		Drs.								
Wall piece	8	8	E. R.	Ball	0 5¼	0·935	1134·8	...	1167·6	3·1
Enfield rifle	3	2·5	,,	M. ball	530 grs.	0·577	1188·7	...	1272·8	0·85
		Lb. oz.			Lb. oz.					
6-pr. Armstrong *	15	0 12	A. 4, W. A.	Seg. shell	6 0	2·585	937·5	...	946·4	37·2
12-pr. Armstrong	10	1 8	,, ,,	,,	11 9	3·084	1180·9	1·000	1190·2	113·6

* The results with the 6-pr. Armstrong require confirmation.

initial velocities of some of the projectiles fired from smooth-bored guns.

To illustrate the application of these constants, we may compare their value for the 12-pr. howitzer and the 12-pr. Armstrong, the velocities of the projectiles fired from these guns being nearly the same, but by the table it appears that the measure of precision in the former case is only about one-fourth of that in the latter case, or in other words, the mean error in initial velocity alone is nearly four times as great. The great irregularity in the initial velocity of the Martin shells is also very conspicuous.

15. The relation between initial velocity, weight of charge, weight of projectile, and length of bore is given (see Didion, *Traité de Balistique*,) by the following equation :—

$$v = \gamma\sqrt{\frac{\mu}{m + \frac{\mu}{\cdot 3}} \cdot \log . \frac{M}{\mu}} - \lambda \frac{C^2 - C'^2}{C^2} \quad . \quad . \quad (7)$$

when V = initial velocity, μ = weight of charge, m = weight of shot, bottom, etc., M = quantity of powder required to fill the bore, C = calibre of gun, C′ = diameter of shot. γ and λ are constants whose values have to be determined by experiment. The second term of the right-hand member of Equation (7) represents the decrement in initial velocity due to windage, and the value of the coefficient λ should be derived from a series of experiments expressly instituted for the purpose. Strictly speaking, this value depends upon a great variety of conditions, but chiefly upon the strength and physical properties of the powder, and upon the length of the bore of the gun. Under normal circumstances, however, the mean value of λ may, with but a very trifling error, be assumed; and General Didion, in his work above referred to, gives $\lambda = 2300$ as the result of the French investigations with the service gunpowder, but an analysis of the above experiments points to a considerably higher value. Indeed, from instances in these experiments, where the variation in windage was sufficiently great, 3158 has been obtained as the mean value of λ, and as this number very nearly agrees with that stated by Colonel Boxer to result from the mean of Major Mordecai's extensive experiments on windage, I have taken as correct the value of λ, viz. 3200, given by that officer.

Assuming λ as above given, γ is easily computed from the data furnished by experiments. γ varies chiefly with the nature and condition of the powder employed, and the annexed table given the values

which have been obtained for the several guns experimented with, and the nature of the powder used in each case.

TABLE 2.—*Values of γ for the undermentioned smooth-bored guns, deduced from the experiments recorded in Table* 1.

Nature of gun.	Nature of powder.	Value of γ.
10-in. gun	L. G., W. A.	3284
68-pr. (95 cwt.)	,, ,,	3491
,, ,,	L. G., Hall & Sons	3536
8-in. gun (65 cwt.)	,, ,,	3307
32-pr. (58 cwt.)	L. G., W. A.	3428
24-pr. (50 cwt.)	,, ,,	3390
18-pr. (38 cwt.)	,, ,,	3454
12-pr. (18 cwt.)	L. G.	3561
9-pr. (13 cwt.)	,,	3422
6-pr. (6 cwt.)	,,	3321
12-pr. howitzer	,,	3291
24-pr. howitzer	,,	3275

The experiments under the discussion show that the equation

$$v = \gamma\sqrt{\frac{\mu}{m + \frac{\mu}{3}} \cdot \log . \frac{\mathrm{M}}{\mu}} - 3200\,\frac{\mathrm{C}^2 - \mathrm{C}'^2}{\mathrm{C}^2} \quad . \quad . \quad (8)$$

gives the velocity due to a variation in the weight either in the charge or projectile with great exactness, the proper value of γ being used in each series, and this equation has therefore been used to calculate the initial velocities of the various projectiles thrown from smooth-bored guns.

These velocities may be depended upon as correct (supposing the same powder to be used) within very narrow limits, and the computed velocities are in this case perhaps preferable to direct determinations, as, unless the whole series for each gun were carried on at the same time, and with powder of exactly the same nature and date of manufacture, discrepancies from variations in the strength of the powder would be sure to arise.

[TABLE 3

Table 3.—*Showing the initial velocities of the* various service projectiles fired from the undermentioned guns. The velocities marked * are observed; the remainder are calculated from the data furnished by the observed velocities.*

Nature of Ordnance.	Calibre.	Charge.	Projectile.		Windage.	Initial velocity.	Initial energy.
			Nature.	Weight.			
	"	Lbs.		Lbs.	"	F. S.	F. T.
10-gun (87 cwt.) .	10	12	Hol. shot	88·475	·142	1270·4*	990·0
,, ,, .	10	8	Mar. shell	117·14	·1425	930·1*	702·8
,, ,, .	10	12	Com. shell	92·625	·15	1257·5	1015·1
,, ,, .	10	12	Case	77·625	·18	1353·7	986·3
,, ,, .	10	12	Grape	83·375	·18	1308·1	989·3
68-pr. (95 cwt.) .	8·12	16	Shot	66·224	·168	1579·0*	1144·9
,, ,, .	8·12	16	Nav. shell	51·5	·17	1809·9*	1169·8
,, ,, .	8·12	16	Com. shell	49·875	·226	1790·7*	1109·0
,, ,, .	8·12	10	Mar. shell	60·0	·235	1308·5*	712·3
,, ,, .	8·12	16	Diaph. shell	60·75	·195	1627·9	1116·3
,, ,, .	8·12	16	Case	45·687	·265	1818·1	1047·2
,, ,, .	8·12	16	Grape	66·5	·3	1475·3	1003·6
8-gun (65 cwt.) .	8·05	10	Hol. shot	46·007	·21	1487·9*	706·3
,, ,, .	8·05	10	Com. shell	49·875	·194	1464·4*	741·6
,, ,, .	8·05	10	Mar. shell	51·5	·13	1506·4*	810·4
,, ,, .	8·05	10	Diaph. shell	60·75	·125	1356·9	775·6
,, ,, .	8·05	10	Case	45·687	·195	1712·7	929·3
,, ,, .	8·05	10	Grape	66·5	·23	1214·4	680·0
32-pr. (58 cwt.) .	6·375	10	Shot	31·375	·196	1690·0*	621·4
,, ,, .	6·375	8	,,	31·389	·194	1618·7*	570·3
,, ,, .	6·375	6	,,	31·349	·195	1447·5*	455·5
,, ,, .	6·375	10	Com. shell	24·312	·198	1912·6	616·7
,, ,, .	6·375	10	Diaph. shell	28·75	·198	1762·4	619·2
,, ,, .	6·375	10	Case	36·094	·228	1543·8	596·5
,, ,, .	6·375	10	Grape	36·25	·228	1540·3	596·4
24-pr. (50 cwt.) .	5·823	8	Shot	23·047	·208	1720·5*	482·2
,, ,, .	5·823	8	Com. shell	17·5	·228	1948·2	460·4
,, ,, .	5·823	8	Diaph. shell	20·875	·228	1786·0	461·7
,, ,, .	5·823	8	Case	25·594	·2435	1594·7	451·3
,, ,, .	5·823	8	Grape	26·0	·253	1571·6	445·3
18-pr. (38 cwt.) .	5·292	6	Shot	17·656	·205	1690·6*	349·9
,, ,, .	5·292	6	Com. shell	13·125	·193	1971·6	353·8
,, ,, .	5·292	6	Diaph. shell	15·875	·193	1797·3	355·6
,, ,, .	5·292	6	Case	19·562	·218	1588·5	342·3
,, ,, .	5·292	6	Grape	19·5	·218	1591·2	342·3
12-pr. (18 cwt.) .	4·623	4	Shot	12·656	·803	1769·8*	274·9
,, ,, .	4·623	4	Com. shell	9·0	·169	1987·4	246·5
,, ,, .	4·623	4	Diaph. shell	10·375	·169	1854·7	247·5
,, ,, .	4·623	4	Case	16·625	·159	1469·8	249·0
9-pr. (13 cwt.) .	4·2	2·5	Shot	9·359	·1	1613·7*	169·0
,, ,, .	4·2	2·5	Diaph. shell	8·062	·12	1707·3	162·9
,, ,, .	4·2	2·5	Case	13·0	·1315	1318·8	156·8
6-pr. (6 cwt.) .	3·668	1·5	Shot	6·23	·1	1484·5*	95·2
,, ,, .	3·668	1·5	Diaph. shell	5·125	·118	1608·8	92·0
,, ,, .	3·668	1·5	Case	8·5	·1275	1215·8	87·1
12-pr. howr. (6½ cwt.)	4·58	1·25	Com. shell	9·0	·126	1144·6*	81·7
,, ,,	4·58	1·25	Diaph. shell	10·465	·126	1058·1	81·2
,, ,,	4·58	1·25	Case	8·118	·148	1185·5	79·1
24-pr. howr. (12 cwt.)	5·72	2·5	Com. shell	17·5	·125	1222·9*	181·4
,, ,,	5·72	2·5	Diaph. shell	20·875	·125	1113·0	179·2
,, ,,	5·72	2·5	Case	14·014	·15	1369·9	182·4

* The mean weights and windages of the various projectiles have been taken.

DIAGRAM SHEWING THE INITIAL VELOCITIES OF A 12 P^R. ARMSTRONG PROJECTILE AS A FUNCTION OF THE WEIGHT OF THE CHARGE.

Note. Black Lines shew observed velocities.
Red Lines shew computed velocities.

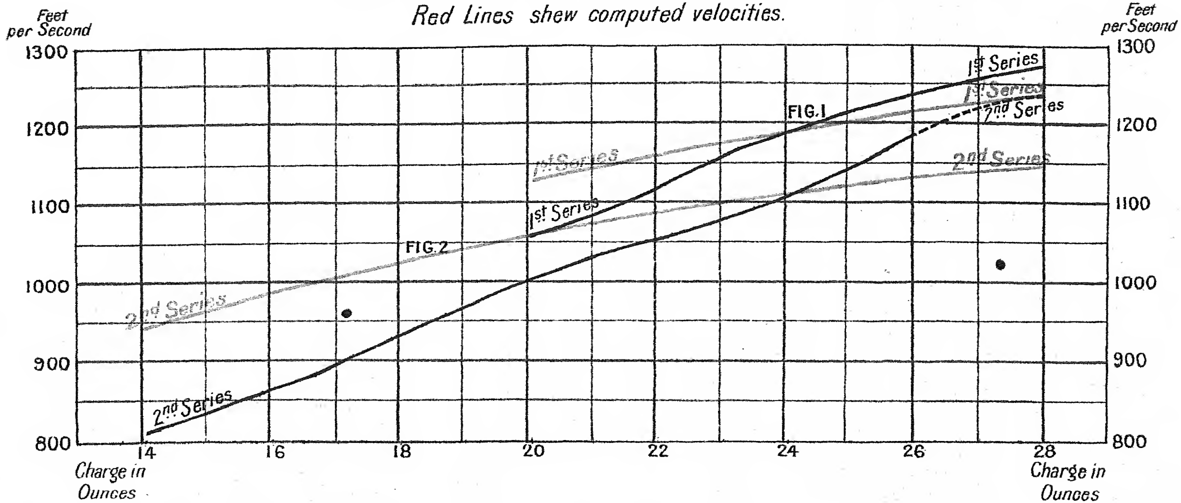
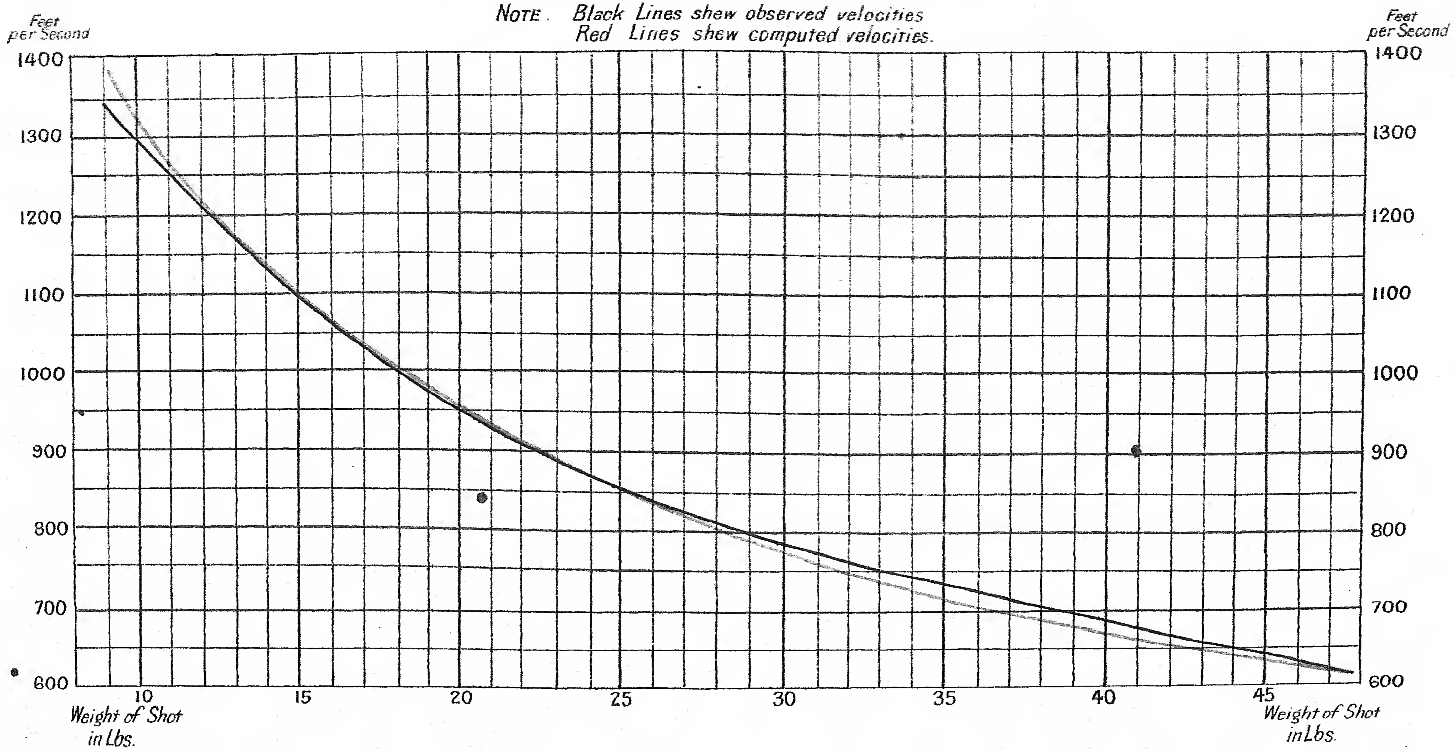


Fig. 3.

DIAGRAM SHEWING THE INITIAL VELOCITIES OF PROJECTILES FIRED FROM A 12 P^R ARMSTRONG GUN AS A FUNCTION OF THE WEIGHT OF THE SHOT.

Note. Black Lines shew observed velocities
Red Lines shew computed velocities.



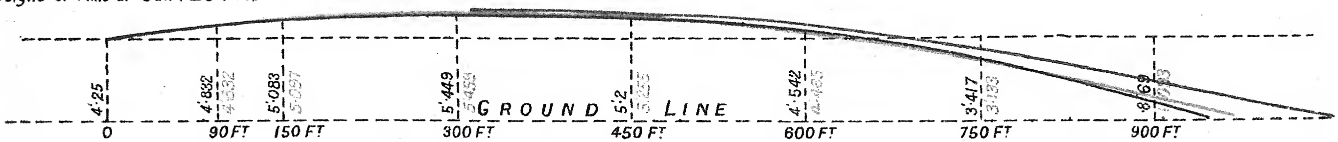
TRAJECTORIES OF 12 P^{R} ARMSTRONG GUN N^{o} 224 FIRED WITH SERVICE CHARGES.

From Experiments made Sep^{t} 10th & 15th 1860.

Mean of 6 Rounds.

Initial Velocity 1197·5 Feet per Second
Angle of Departure 0° 25′–44″
Range 938 Feet.
Gun laid point blank, Angle of Elevation 0′.0″
Height of Axis of Gun 4·25 Feet

Scale of Abscissae 166 Feet to an Inch
" " Ordinates 10 Feet to an Inch

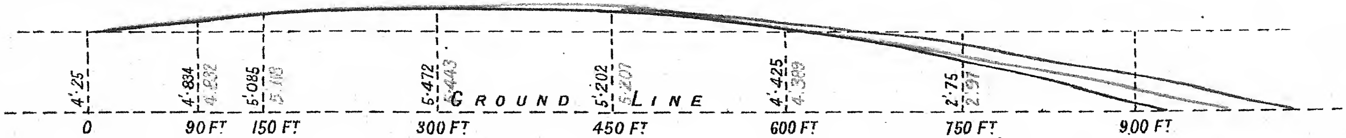


Note:—

Black Lines shew observed path of Projectiles
Blue. Lines shew Path in Vacuo
Red Lines shew Path calculated on the assumption of the resistance of the air $= \cdot 0005213\,\pi.r^2 v^2 \left(1 + \frac{v}{1426\cdot 4}\right)$

Mean of 5 Rounds.

Initial Velocity 1179·8 Feet per Second
Angle of Departure 0°25′–55″
Range 897 Feet.
Gun laid point blank, Angle of Elevation 0′.0″
Height of Axis of Gun 4·25 Feet



TRAJECTORY OF 12 PR. ARMSTRONG GUN No. 224 FIRED WITH SERVICE CHARGES.

At an Apparent Elevation of 0° 30'

From Experiments Made Sept. 19th. 1860.

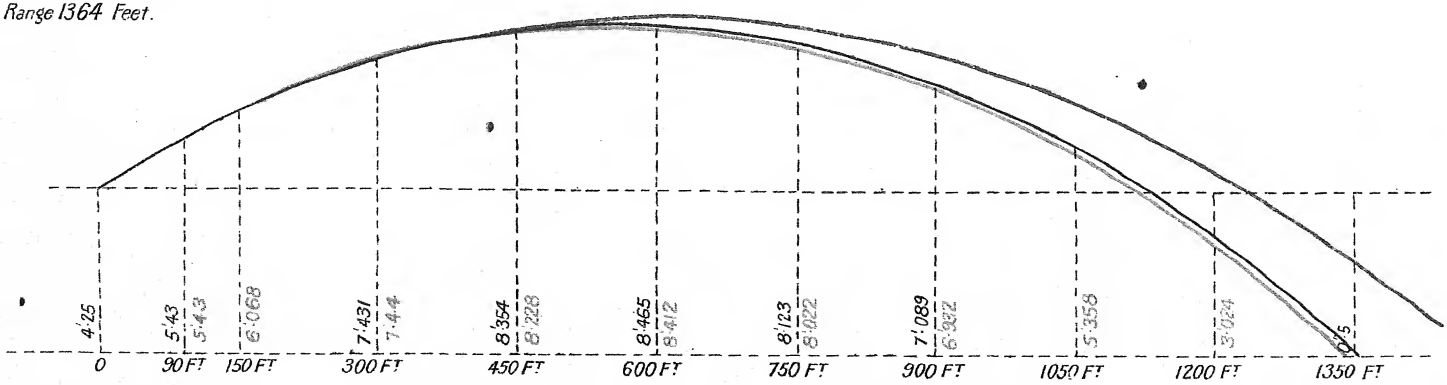
NOTE

Black Line shews observed Path of Projectile.
Blue Line shews path in Vacuo.
Red Line shews path calculated on the assumption of the resistance of the air $= \cdot 0005213\ \pi R^2 V^2 \left(1 + \frac{V}{1426 \cdot 4}\right)$

Mean of 4 Rounds.

Initial Velocity **1188·9** *Feet per Second.*
Angle of Departure 0° 48' 35".
Gun laid at an Elevation of 0° 30' 0".
Range 1364 Feet.

Scale of Abscissae 208 Feet to an Inch
" " Ordinates 5 " " " "



Variation of the initial velocity of the 12-*pr. Armstrong in terms of the weight of the charge.*

16. The decrease in the range of the 12-pr. Armstrong, due to a slight reduction of the charge, had not, in experimental practice, escaped the notice of the Ordnance Select Committee, and it became a point of interest to determine the dependence of the initial velocity on the charge, and to ascertain if it followed even approximately the same laws as have been laid down for smooth-bored guns.

17. The experiments, an abstract of which is given in the first series of Table 4, were undertaken with this view; but in laying down in the form of a diagram the results thus obtained, marked differences were found to exist, which will best be understood by comparing the two curves delineated in Plate II., Fig. 1, in the accompanying diagram. The black line in this diagram shows the relation of the initial velocity to the charge as derived from this series by actual observation, while the red line denotes the hypothetic relation as determined from the equation

$$v = 3230{\cdot}8\sqrt{\frac{\mu}{m+\frac{\mu}{3}}\log.\frac{18{\cdot}5}{\mu}}$$

where μ and m denote the weight of the charge and shot in pounds, the value of the constant in this equation being determined from the velocity when the service charge of 1 lb. 8 oz. was employed.

It will be observed that while the hypothetic curve is always concave to the line of abscissæ, in the curve derived from actual observation there are two points of inflexion, it being in one portion of its trace convex instead of concave to the axis of x.

18. To check the results obtained in this series, a second series with another gun was subsequently made, the abstract of which is given in the second series, Table 4. Their graphical representation is delineated in Plate II., Fig. 2, in which, as before, the black line denotes the observed curve, the red the computed one, the value of v being given by the equation

$$v = 3026{\cdot}6\sqrt{\frac{\mu}{m+\frac{\mu}{3}}\log.\frac{18{\cdot}5}{\mu}}$$

the coefficient in this case, as in the former, having been determined from the data furnished in the case where the service charge was used.

19. Although in this second case the initial velocities are, owing to powder of a different strength having been used, very considerably under the velocities in the former case, it will be noticed that the same

peculiarities are observable, there being a portion of the curve with its convexity turned towards the axis of abscissæ.

20. The cause of the wide departure from the normal law exhibited in these diagrams is easily explained. It will be remembered that in the Armstrong gun, the shot always occupies a definite position in the bore, the service charge nearly filling the powder-chamber. Hence it follows that if reduced charges be used, additional air space is left in the chamber, so that in addition to the decrement of velocity due to reduction in the charge there is to be added the decrement due to the increased air space, and it is easy to see how the combination of these conditions may produce the abnormal results alluded to.

21. The annexed table gives an abstract of the results of these experiments, and I also attach a table giving for powder of average strength the initial velocities for various charges.

TABLE 4.—*Abstract of the results of experiments to ascertain the initial velocity of 12-pr. Armstrong projectiles in terms of the weight of the charge.*

Armstrong 12-pr.	No. of rounds.	Charge.	Projectile. Weight.	Projectile. Diameter.	Velocity at 30 yards.	Initial velocity.	Initial energy.
		Lb. oz.	Lbs. oz.		F. S.	F. S.	F. T.
No. 224	10	1 4	11 9	3·084	1055·3	1063·1	90·6
,,	10	1 6	11 9	3·085	1092·4	1100·7	97·1
,,	10	1 8	11 9	3·084	1180·9	1190·2	113·6
,,	10	1 10	11 9	3·084	1224·8	1234·6	122·2
,,	10	1 12	11 9	3·084	1262·0	1272·2	129·7
No. 1050	10	0 14	11 9	3·084	803·8	809·2	52·5
,,	10	1 0	11 9	3·084	863·9	870·0	60·7
,,	10	1 2	11 9	3·084	924·6	931·1	69·5
,,	10	1 4	11 9	3·084	997·8	1005·1	81·0
,,	10	1 6	11 9	3·084	1050·2	1058·0	89·7
,,	10	1 8	11 9	3·084	1106·4	1114·8	99·6
,,	10	1 10	11 9	3·084	1178·0	1187·3	113·0

TABLE 5.—*Showing the velocity of a 12-pr. Armstrong projectile in relation to the weight of the charge.*

Weight of charge.	Initial velocity.	Initial energy.	Weight of charge.	Initial velocity.	Initial energy.	Weight of charge.	Initial velocity.	Initial energy.
Lb. oz.	F. S.	F. T.	Lb. oz.	F. S.	F. T.	Lb. oz.	F. S.	F. T.
0 14	870	60·7	1 3	1036	86·0	1 8	1190	113·5
0 15	908	66·1	1 4	1063	90·5	1 9	1214	118·1
1 0	943	71·3	1 5	1087	94·7	1 10	1234	122·1
1 1	976	76·4	1 6	1119	100·4	1 11	1254	126·1
1 2	1007	81·3	1 7	1155	106·9	1 12	1272	129·7

The weight of the projectile for this table is 11 lbs. 9 oz.

Variation in the initial velocity of the Armstrong projectiles in terms of the weight of the shot.

22. From the considerations mentioned in the foregoing paragraph, it would naturally be expected that if the weight of the shot be varied instead of that of the charge, there would be a much smaller discrepancy between the computed and the observed velocities, as in this case, the charge remaining the same, there will be no variation in the amount of air space in the powder-chamber.

23. The series given in Table 6 were undertaken with a view to elucidate this point. A graphical representation of the observed and computed velocities is delineated in Plate III., p. 32, the computed velocities being obtained from

$$v = 3358{\cdot}9 \sqrt{\frac{\mu}{m + \frac{\mu}{3}} \log . \frac{18{\cdot}5}{\mu}}$$

and a glance will show how closely in this case the observed velocities accord with the hypothetical ones.

At one point only (where the 9 lbs. projectiles were used) is there any appreciable difference, and this difference is capable of the same explanation as has already been given in par. 20, as, from the construction of this projectile, a greater air space was left in the powder-chamber than in the case of the other projectiles, the position of the base of all of which in the bore of the gun was identically the same.

The annexed tables, 6 and 7, exhibit an analysis of the results obtained from these experiments.

TABLE 6.—*Abstract of the results of the experiments made to determine the initial velocity of projectiles fired from the* 12-*pr. Armstrong gun, the weight of the shot being varied.*

Armstrong 12-pr.	No. of rounds.	Charge.		Projectile.			Velocity at 30 yards.	Initial velocity.		Initial energy.
				Weight.		Diameter.		Observed.	Computed.	
		Lb.	oz.	Lbs.	oz.		F. S.	F. S.	F. S.	F. T.
No 224	11	1	8	11	13	3·084	1164·5	1173·4	...	112·8
,,	11	1	8	11	5	3·084	1192·9	1202·5	...	113·4
,,	10	1	8	10	13	3·084	1209·8	1220·1	...	111·6
No. 1050	5	1	8	9	0	3·074	1322·3	1336·3	1384·0	111·4
,,	6	1	8	11	9	3·084	1227·4	1237·2	1237·0	122·7
,,	6	1	8	24	6	3·084	853·9	856·7	860·3	125·1
,,	6	1	8	35	14	3·084	720·0	721·5	710·1	129·5
,,	5	1	8	47	13	3·084	613·9	614·8	618·1	125·2

TABLE 7.—*Showing the velocity of projectiles of various weights fired from a 12-pr. Armstrong gun.*

Charge.		Weight of shot.		Initial velocity.	Initial energy.	Charge.		Weight of shot.		Initial velocity.	Initial energy.	Charge.		Weight of shot.		Initial velocity.	Initial energy.
Lb.	oz.	Lbs.	oz.	F. S.	F. T.	Lb.	oz.	Lbs.	oz.	F. S.	F. T.	Lb.	oz.	Lbs.	oz.	F. S.	F. T.
1	8	9	0	1380	118·8	1	8	22	0	900	123·5	1	8	35	0	730	129·3
1	8	10	0	1321	121·0	1	8	23	0	881	123·8	1	8	36	0	720	129·4
1	8	11	0	1266	122·2	1	8	24	0	864	124·2	1	8	37	0	710	129·3
1	8	12	0	1213	122·4	1	8	25	0	850	125·2	1	8	38	0	700	129·2
1	8	13	0	1174	124·2	1	8	26	0	835	125·7	1	8	39	0	691	129·1
1	8	14	0	1134	124·8	1	8	27	0	827	128·0	1	8	40	0	682	128·0
1	8	15	0	1095	124·7	1	8	28	0	810	127·4	1	8	41	0	673	128·7
1	8	16	0	1060	124·6	1	8	29	0	797	127·7	1	8	42	0	664	128·4
1	8	17	0	1027	124·3	1	8	30	0	785	128·2	1	8	43	0	655	127·9
1	8	18	0	997	124·0	1	8	31	0	773	128·4	1	8	44	0	646	127·3
1	8	19	0	970	123·9	1	8	32	0	762	128·8	1	8	45	0	638	127·0
1	8	20	0	945	123·8	1	8	33	0	751	129·0	1	8	46	0	630	126·6
1	8	21	0	923	124·0	1	8	34	0	740	129·1	1	8	47	0	622	126·1

Variation in initial velocity between high and low gauge projectiles (Armstrong).

24. The experiments in Table 8 were made with a view to ascertain whether there is any difference in velocity between projectiles of the highest and lowest gauges admitted into the service.

The results are here given, and it will be seen that there exists between the velocities no appreciable difference.

TABLE 8.—*Abstract of the results of the experiments made to ascertain the difference in initial velocity between high and low gauge projectiles.*

Armstrong 12-pr.	No. of rounds.	Charge.		Projectile. Weight.		Projectile. Diam.	Velocity at 30 yards.	Initial velocity.	Remarks.	Initial energy.
		Lb.	oz.	Lbs.	oz.		F. S.	F. S.		F. T.
No. 224	5	1	8	11	9	3·080	1184·1	1193·4	Bore washed	114·1
,,	6	1	8	11	9	3·085	1177·2	1186·5		112·9
,,	11	1	8	11	9	3·080	1184·1	1193·4	Lubricating wads used	114·1
,,	8	1	8	11	9	3·085	1187·8	1197·1		114·8

25. In the series of which an abstract, Table 9, follows, are given the comparative initial velocities of the old (A) and new (Q) pattern 12-pr. shells, both with and without lubricating wads.

It will be seen that while the old pattern shell has, although scarcely appreciable, a slightly higher initial velocity, due to the greater diameter at the back end, the introduction of the lubricating wads adds to the velocity about 15 feet.

The effect of the greater diameter at the back end will be again referred to; but it is interesting to observe that while the initial velocity is increased by offering, in the first instance, increased resistance to the motion of the projectile, it is also increased by diminishing as much as possible the resistance of the friction in its passage through the bore. The explanation of these results is too obvious to require remark.

TABLE 9.—*Abstract of experiments made to ascertain the difference in initial velocity of old and new pattern 12-pr. shells, with and without lubricating wads.*

Armstrong 12-pr.	No. of rounds.	Charge.	Projectile.		Velocity at 30 yards.	Initial velocity.	Remarks.	Initial energy.
			Weight.	Diam.				
		Lb. oz.	Lbs. oz.		F. S.	F. S.		F. T.
No. 224	15	1 8	11 9	3·072	1154·2	1163·2	Q. Pattern shell lubricating wad	108·4
,,	14	1 8	11 9	3·085	1157·1	1166·1	A. Pattern shell lubricating wad	109·0
,,	13	1 8	11 9	3·072	1142·0	1150·8	Q. Pattern shell bore washed	106·1
,,	10	1 8	11 9	3·085	1140·6	1149·4	A. Pattern shell bore washed	105·9

26. Table 10 gives an abstract of the experiments made to compare the initial velocities of shell of the same form and weight, fired from rifled and smooth-bored 32-prs. of 58 cwt. The ribbed shell was, in the first case, fired from the rifled gun. Shells of the same form, diameter, and weight, but with the ribs removed, were then fired from the rifled gun, and finally similar shells were fired from a smooth-bored 32-pr.

TABLE 10.—*Abstract of experiments to ascertain the comparative velocities of the same shell, fired from rifled and smooth-bored 32-prs. of 58 cwt.*

Nature of gun.	Charge.	Projectile.			Velocity at 30 yards.	Initial velocity.	Remarks.
		Nature.	Weight.	Diameter.			
	Lbs. oz.		Lbs. oz.				
32-pr., rifled .	5 8	Pl. shell	54 0	6·350	1215·7	1224·5	...
,, ,, .	5 8	,,	54 0	6·350	1122·1	1135·3	Ribs of shell removed.
32-pr., 58 cwt.	5 8	,,	54 0	6·350	1187·4	1201·7	

The velocities in these three cases were respectively 1224·5, 1135·3, and 1201·7 feet per second. The great difference in velocity in the second case is due to the escape of gas by the grooves in the rifled gun.

27. With the same rifled 32-pr. gun, experiments were also made to ascertain the reduction in the initial velocity due to an elongation in the cartridge, and the results of these experiments are here tabulated.

TABLE 11.—*Abstract of experiments made to ascertain the initial velocities of projectiles fired from a 32-pr. rifled shunt gun, with charges made up in cartridges of various lengths.*

Nature of gun.	No. of rounds.	Cartridge.		Projectile.			Velocity at 30 yards.	Initial velocity.
		Charge.	Length.	Nature.	Weight.	Diameter.		
		Lbs. oz.	Inches.		Lbs. oz.			
Rifled 32-pr.	4	5 8	12	Pl. shell	54 0	6·350	1054·6	1061·7
,,	3	5 8	9	,,	54 0	6·350	1076·8	1084·2
,,	1	5 8	8	,,	54 0	6·350	1102·2	1109·8
,,	1	5 8	7·5	,,	54 0	6·350	1114·5	1122·3
,,	2	5 8	6	,,	54 0	6·350	1187·9	1196·4

From the rapid increase in the initial velocity shown in this table, due to the reduction in the length of the cartridge, the effect of the variation in air space in the 12-pr. Armstrong, to which I have already alluded, will be easily understood.

28. The experience of the preceding practice, together with theoretical considerations, having pointed to a probable decrease in velocity should the diameter of B.L. projectiles be diminished or reduced to that of the bore, the experiments, of which an abstract is given in Table 12, were undertaken with the object of corroborating or discovering this view.

From the abstract of this interesting series it will be seen that while the velocity of the projectiles under normal circumstances was 1248·2 feet per second, when their diameter was reduced to that of the bore, with the exception of a narrow band at the back end, it became only 1209·7 feet per second; and when the diameter was finally reduced throughout to that of the bore, it was reduced to 1172·8 feet. In the rounds fired with the reduced diameters, the projectiles in all cases appeared to be perfectly steady in flight.

TABLE 12.—*Abstracts of experiments made to determine the effect on the initial velocity of diminishing the lead on the* 12-*pr. Armstrong projectiles.*

Armstrong 12-pr.	No. of rounds.	Charge.	Projectile.		Velocity at 30 yards.	Initial velocity.	Remarks.
			Weight.	Diam.			
		Lb. oz.	Lbs. oz.				
No. 1050	4	1 8	11 9	3·074	1238·3	1248·2	Shell fired under normal circumstances.
,,	2	1 8	11 9	3·010	1200·2	1209·7	Same shell reduced to the diameter of 3·01, with the exception of a ring at the base ·25 inches broad.
,,	2	1 8	11 9	3·010	1163·7	1172·8	Same shell reduced throughout.

29. The experiments with the Armstrong 12-pr. having been chiefly carried on with the same gun, the initial velocities obtained under similar circumstances become a measure of the variability, in strength, of the service gunpowder, and it is somewhat surprising to find so great a variation in powder recently made and professedly of the same make. For illustration of this remark, I might point to the differences in initial velocity exhibited in Plate II., Figs. 1 and 2. In this case, it is true, the results were obtained from different guns; but under similar circumstances, these guns were found to give nearly identical velocities. Another even stronger case, however, may be taken from the velocities given on different occasions by the gun numbered 1050. Thus, on the 12th March 1861, with a service charge of powder marked (A. 4, W.A., 5/9/60, lot 288), the initial velocity was found to be 1114·8 feet, while under precisely the same circumstances, on the 15th March 1861, with powder marked (A. 4, Hall and Sons, 11/7/60, lot 2), the initial velocity was 1248·2 feet per second. I may observe that with the Armstrong 12-pr., when the same powder is used, the variation in initial velocity is very slight, the extreme difference in ten rounds rarely exceeding 20 feet.

30. On actual service it is obvious that the strength of the powder may be expected to vary considerably more than is here indicated; and I venture to draw the attention of the Select Committee to this point, as one seriously affecting the precision of rifled, or indeed of any guns, and as a case in which the electro-ballistic apparatus might be most advantageously employed.

31. My attention during these experiments was early drawn to the ranges obtained at P. B., and at small angles of elevation, with

the 12-pr. Armstrong. These ranges considerably exceeded those of the smooth-bored field-service guns, although, of course, the initial velocity in these latter is very much higher. I therefore took the usual steps for ascertaining the "angle of departure," and, as much additional trouble was not entailed, I also made arrangements for ascertaining the ordinates at various points of the trajectory. It will be seen by these observations that the angle of projection of a projectile fired from a 12-pr. gun, accurately laid with its bore horizontal, varied from 0°23′30″ to 0°28′28″, the mean angle of projection being 25′33″; while in the same gun fired with an elevation of 30′, the angle of projection varied from 47′0″ to 49′6″, the mean angle being 48′18″.

In Plates III., IV., and V., p. 32, I have laid down, for the information of the Committee, the mean results of this practice, the observed trajectories being denoted by black, the computed by red, and for the sake of comparison I have also shown, in blue lines, the departure of both curves from the parabolic.

The annexed abstract, Table 13, will show how close is the agreement between the computed and observed ordinates in the curves delineated; while a similar comparison for the majority of the curves observed is made in the detailed report of the practice furnished to the Committee.

Table 13.—*Abstract of the results of the experiments made to ascertain the angle of projection and the trajectories of the 12-pr. Armstrong projectiles when fired P.B., and at an apparent elevation of 30′.*

Elevation given.	Angle of departure.	Velocity at 30 yards.	Initial velocity.	Ordinates at 90 feet. Obs.	90 feet. Com.	150 feet. Obs.	150 feet. Com.	300 feet. Obs.	300 feet. Com.	450 feet. Obs.	450 feet. Com.
° ′	° ′ ″	F. S.	F. S.								
0 0	0 25 44	1188·1	1197·5	4·832	4·832	5·083	5·097	5·444	5·459	5·2	5·255
0 0	0 25 55	1170·7	1179·8	4·834	4·832	5·085	5·118	5·472	5·443	5·202	5·207
0 30	0 48 35	1179·6	1188·9	5·431	5·441	...	...	7·421	7·44	8·359	8·329

Ordinates at—*Continued.*

600 feet. Obs.	600 feet. Com.	750 feet. Obs.	750 feet. Com.	900 feet. Obs.	900 feet. Com.	1050 feet. Obs.	1050 feet. Com.	1200 feet. Obs.	1200 feet. Com.	1355 feet. Obs.	1355 feet. Com.
4·527	4·483	3·417	3·133	·869	1·003	...	...	...	...	...	...
4·425	4·359	2·75	2·97	...	...	...	...	...	...	...	...
8·465	8·414	8·133	8·025	7·089	7·056	...	5·428	...	3·033	0·45	0·01

32. The ordinates in Table 13 were calculated on the hypothesis that the resistance of the air was given by the equation

$$\text{resistance} = \cdot 0005213\pi R^2 v^2 \frac{\delta}{534\cdot 3}\left\{1 + \frac{v}{1 + 1426\cdot 4}\right\}$$

The accordance of the ordinates calculated on this hypothesis are, on the whole, exceedingly close; but it would be unwise to place too much dependence on the results of experiments so partial, and carried on at such low angles.

33. The following table gives an abstract of the results of several miscellaneous experiments :—

TABLE 14.

Nature of gun.	Charge.	Projectile			Velocity at 30 yards.	Initial velocity.	Remarks.
		Nature.	Weight.	Diam.			
	Lb. oz.		Lbs. oz.				
9-pr., brass 13½ cwt.	0 14	Shot	9 5	4·080	1011·2	...	At 25 yards.
	1 8	,,	9 5	4·080	1310·9	...	
12-pr., 8½ cwt., Armstrong	1 2	S. shell	9 0	3·074	1130·0	1141·2	Experiments to ascertain the initial velocity of a 9-pr. shell with a charge of 1 lb. 2 oz.
12-pr., 6 cwt., Armstrong	1 6	,,	11 9	3·074	1103·4	1111·8	Experiments to ascertain the initial velocities of 12-pr. shells fired from a 12-pr. gun of 6 cwt.
12-pr., 8½ cwt., Armstrong No. 8	1 8	,,	11 9	3·084	1127·6	1136·3	Experiments to ascertain the difference in initial velocity and regularity of two 12-prs., the first of which had been exposed to the weather for several weeks.
12-pr., 8½ cwt., Armstrong No. 224	1 8	,,	11 9	3·084	1141·8	1150·6	
Experiments to ascertain the initial velocity of the old pattern (25 *lbs.*) *projectiles fired from* 20-*pr. guns.*							
	Lbs. oz.		Lbs. oz.				
Long 25-pr. Armstrong R. G. H. No. 384	2 8	S. shell	25 0	3·830	963·8	968·8	Without lubricating wads.
	2 8	,,	25 0	3·830	1014·4	1019·8	Lubricating wads used.
	2 13	,,	25 0	3·830	1083·3	1089·3	
	3 2	,,	25 0	3·830	1136·1	1142·5	
Short 25-pr. Armstrong No. 403	2 6	,,	25 0	3·830	874·5	878·9	

III.

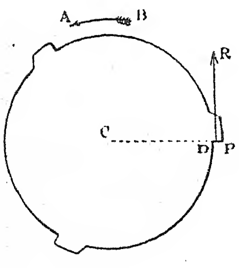
ON THE RATIO BETWEEN THE FORCES TENDING TO PRODUCE TRANSLATION AND ROTATION IN THE BORES OF RIFLED GUNS.

(*Philosophical Magazine, September* 1863.)

THE magnitude which the rifled ordnance of the present day have attained, and the large charges which are consumed in their bores, render it an object of great interest that we should be able to assign the pressures on the grooves (or other driving-surfaces intended to give rotation) due to different modes of rifling, as well as to determine the increment in the gaseous pressure arising from the nature of rifling adopted.

The formulæ which I shall hereafter give, have, with slight modifications, been used at Elswick for nearly three years, and are now given, partly because no investigation of the question has, to my knowledge, been published, and partly because, as several erroneous statements on the subject have appeared, the formulæ themselves may possibly be of use to some artillerists.

Fig. 1.



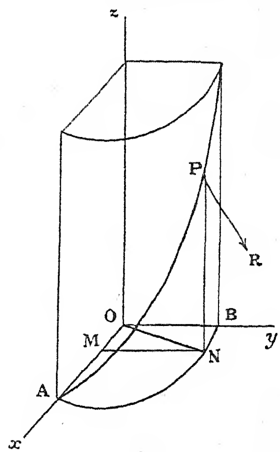
The case we shall first examine will be that in which the rotation is given by means of grooves, the driving-surfaces of which are such that if a section of the gun, perpendicular to the axis, be made, the line drawn from the centre of the bore to the groove is coincident with the section of the driving-surface. A section of such a form of rifling is shown in Fig. 1. The reader is supposed to be looking from the muzzle towards the breech of the gun, and the direction of rotation is shown by the arrow AB.

It will be seen that the radius CD is coincident with the section of the driving-surface DP.

In entering upon this investigation, it will be more convenient to consider the projectile in its motion along the bore of the gun as moving on a fixed axis, and, further, to suppose that the motion of rotation is communicated to the projectile by a single groove. These suppositions will not interfere with the accuracy of our results, and will enable us very much to simplify the equations of motion.

Take (Fig. 2) as the plane of xy, the plane passing through the commencement of the rifling at right angles to the axis of the gun. Let the axis of x pass through the groove under consideration, and let the axis of z be that of the gun. Let AP be the helix, and let (see Figs. 1 and 2) P (xyz) be the point at which the resultant of all the pressures on the groove may be assumed to act, the projectile being in a given position. Let the angle AON $= \phi$.

Fig. 2.



Let us now consider the forces which act upon the projectile. We have, first, the gaseous pressure acting on the base of the shot. Let us call this force, the resultant of which acts along the axis of z, G. Secondly, if R be the pressure between the projectile and the groove at the point P, this pressure will be exerted normally to the surface of the groove, and if we denote by λ, μ, ν the angles which the normal makes with the co-ordinate axes, the resolved parts of this force will be

$$R \, . \cos \lambda, \quad R \, . \cos \mu, \quad R \, . \cos \nu$$

Thirdly, if μ_1 be the coefficient of friction between the rib of the projectile and the driving-surface, the force $\mu_1 R$ will tend to retard the motion of the projectile. This force will act along the tangent to the helix which the point P describes; and if α, β, γ be the angles which the tangent makes with the co-ordinate axes, we have as the resolved portions of this force $\mu_1 R \, . \cos \alpha$, $\mu_1 R \, . \cos \beta$, $\mu_1 R \, . \cos \gamma$; and summing up these forces, we have the forces which act

$$\left.\begin{array}{l} \text{parallel to } x = X = R\{\cos\lambda - \mu_1 \cos\alpha\} \\ \text{parallel to } y = Y = R\{\cos\mu - \mu_1 \cos\beta\} \\ \text{parallel to } z = Z = G + R\{\cos\nu - \mu_1 \cos\gamma\} \end{array}\right\} \quad . \quad . \quad (1)$$

and the equations of motion will be

$$M \cdot \frac{d^2z}{dt^2} = G + R \cdot \{\cos \nu - \mu_1 \cos \gamma\} \quad . \quad . \quad . \quad (2)$$

$$\frac{d^2\phi}{dt^2} = \frac{Yx - Xy}{M\rho^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

ρ being the radius of gyration.

We proceed to determine the value of the angles α, β, γ, λ, μ, ν. Let the equations to the helix described by the point P be put under the form

$$x = r \cdot \cos \phi, \quad y = r \sin \phi, \quad z = kr\phi \quad . \quad . \quad . \quad (4)$$

k being the tangent of the angle at which the helix is inclined to the plane of xy. Then

$$dx = -r \sin \phi d\phi, \quad dy = r \cos \phi d\phi, \quad dz = krd\phi$$

$$ds = r\sqrt{1+k^2} \cdot d\phi$$

and

$$\left.\begin{aligned} \cos \alpha &= \frac{dx}{ds} = \frac{-\sin \phi}{\sqrt{1+k^2}} \\ \cos \beta &= \frac{dy}{ds} = \frac{\cos \phi}{\sqrt{1+k^2}} \\ \cos \gamma &= \frac{dz}{ds} = \frac{k}{\sqrt{1+k^2}} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

To determine the values of λ, μ, ν, we shall first seek the equation to the driving-surface of the groove. In the case under consideration, the surface is a well-known conoidal one, the "skew helicoid," and is familiar to the eye as the under surface of a spiral staircase. It is generated by a straight line which passes through the axis of z, always remains perpendicular to it, and meets the helix described by the point P. The equations to the director being given in (4), if x_1, y_1, z_1 be the current co-ordinates of the generator, its equations are

$$x_1 y - y_1 x = 0, \quad z_1 = z \quad . \quad . \quad . \quad . \quad (6)$$

Hence

$$x = r \cdot \cos \frac{z_1}{kr}, \quad y = r \sin \frac{z_1}{kr}$$

and the equation to the surface is

$$y_1 \cdot \cos \frac{z_1}{kr} - x_1 \cdot \sin \frac{z_1}{kr} = 0$$

or, dropping the suffixes,

$$y \,.\cos\frac{z}{kr} - x \,.\sin\frac{z}{kr} = 0 \qquad . \quad . \quad . \quad (7)$$

Now λ, μ, ν being the angles which the normal to (7) makes with the axes,

$$\left.\begin{aligned}
\cos\lambda &= \frac{\left(\frac{d\mathrm{F}}{dx}\right)}{\left\{\left(\frac{d\mathrm{F}}{dx}\right)^2 + \left(\frac{d\mathrm{F}}{dy}\right)^2 + \left(\frac{d\mathrm{F}}{dz}\right)^2\right\}^{\frac{1}{2}}} \\
\cos\mu &= \frac{\left(\frac{d\mathrm{F}}{dy}\right)}{\left\{\left(\frac{d\mathrm{F}}{dx}\right)^2 + \left(\frac{d\mathrm{F}}{dy}\right)^2 + \left(\frac{d\mathrm{F}}{dz}\right)^2\right\}^{\frac{1}{2}}} \\
\cos\nu &= \frac{\left(\frac{d\mathrm{F}}{dz}\right)}{\left\{\left(\frac{d\mathrm{F}}{dx}\right)^2 + \left(\frac{d\mathrm{F}}{dy}\right)^2 + \left(\frac{d\mathrm{F}}{dz}\right)^2\right\}^{\frac{1}{2}}}
\end{aligned}\right\} \qquad . \quad . \quad (8)$$

Now

$$\left(\frac{d\mathrm{F}}{dx}\right) = -\sin\frac{z}{kr}, \quad \left(\frac{d\mathrm{F}}{dy}\right) = \cos\frac{z}{kr}$$

$$\left(\frac{d\mathrm{F}}{dz}\right) = -\frac{1}{k}\left\{\frac{x}{r}\cos\frac{z}{kr} + \frac{y}{r}\,.\sin\frac{z}{kr}\right\}$$

but since in the case we are now considering (xyz) is a point both in the surface given by Equation (7) and in the directing helix, we have from (4),

$$\frac{x}{r} = \cos\phi = \cos\frac{z}{kr}, \quad \frac{y}{r} = \sin\phi = \sin\frac{z}{kr}$$

and

$$\therefore \qquad \left(\frac{d\mathrm{F}}{dz}\right) = -\frac{1}{k}$$

$$\left\{\left(\frac{d\mathrm{F}}{dx}\right)^2 + \left(\frac{d\mathrm{F}}{dy}\right)^2 + \left(\frac{d\mathrm{F}}{dz}\right)^2\right\}^{\frac{1}{2}} = \frac{1}{k}\cdot\sqrt{1+k^2}$$

Hence

$$\left.\begin{aligned}
\cos\lambda &= -\frac{k\sin\phi}{\sqrt{1+k^2}} \\
\cos\mu &= \frac{k\,.\cos\phi}{\sqrt{1+k^2}} \\
\cos\nu &= -\frac{1}{\sqrt{1+k^2}}
\end{aligned}\right\} \qquad . \quad . \quad . \quad . \quad (9)$$

Now substituting the values of the direction cosines given in Equations (5) and (9), in (1), (2), and (3), we have as the equations of motion,

$$M.\frac{d^2z}{dt^2} = G - \frac{R}{\sqrt{1+k^2}}\{\mu_1 k + 1\} \quad . \quad . \quad . \quad (10)$$

$$\frac{d^2\phi}{dt^2} = \frac{Rr}{\sqrt{1+k^2}}.\frac{k-\mu}{M\rho^2} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

and hence the normal pressure on the rib of the projectile,

$$R = \frac{M\rho^2}{r}.\frac{\sqrt{1+k^2}}{k-\mu_1}.\frac{d^2\phi}{dt^2}$$

But if ω be the angular velocity of the projectile, and h be the pitch of the rifling, we have the following relation between the velocities of translation and rotation,

$$\omega = \frac{d\phi}{dt} = \frac{2\pi}{h}\,v = \frac{2\pi}{h}.\frac{dz}{dt}$$

Hence

$$\frac{d^2\phi}{dt^2} = \frac{2\pi}{h}.\frac{d^2z}{dt^2}$$

and

$$R = \frac{M\rho^2}{r}.\frac{\sqrt{1+k^2}}{k-\mu_1}.\frac{2\pi}{h}.\frac{d^2z}{dt^2} \quad . \quad . \quad . \quad (12)$$

Now, substituting in this equation the value of $\frac{d^2z}{dt^2}$ derived from (10), we have

$$R = \frac{2\pi\rho^2}{rh}.\frac{\sqrt{1+k^2}}{k-\mu_1}\left\{G - \frac{R}{\sqrt{1+k^2}}(\mu_1 k + 1)\right\}$$

or

$$\frac{R}{G} = \frac{2\pi\rho^2\sqrt{1+k^2}}{hr(k-\mu_1) + 2\pi\rho^2(\mu_1 k + 1)} \quad . \quad . \quad . \quad (13)$$

And this equation gives the ratio between the pressures producing translation and rotation.

We now proceed to determine the increment of the gaseous pressure due to the resistance, etc., offered by the rifling to the forward motion of the shot. We shall imagine a smooth-bored gun to fire a shot of the same weight as that of the rifled gun. We shall further suppose that the two projectiles are delivered with the same velocity; and we wish to know, the same ballistic

effect being produced by the two guns, what is the increased pressure which the rifled gun has had to sustain. Now the equation of motion in the case of the smooth-bored gun is

$$M\frac{d^2z}{dt^2} = G \quad . \quad . \quad . \quad . \quad . \quad (14)$$

and in the case of the rifled gun,

$$M\frac{d^2z}{dt^2} = G' - \frac{R}{\sqrt{1+k^2}}\{\mu_1 k+1\} \quad . \quad . \quad . \quad (15)$$

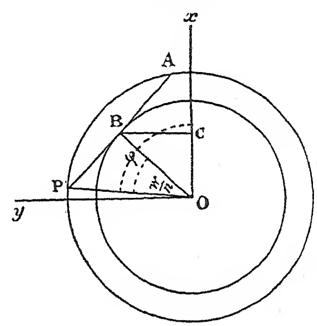
Now, if the velocity-increments in the two cases be taken as equal, we shall have, from Equations (14) and (15),

$$G' = G + \frac{R}{\sqrt{1+k^2}}(\mu_1 k+1) \quad . \quad . \quad . \quad (16)$$

And the second term of the right-hand member of Equation (16) represents the increment of pressure due to the rifling.

Let us now examine the pressures which subsist when a polygonal form of rifling is adopted; and we shall suppose the polygon to have n sides.

Fig. 3.



The equations of motion given in Equations (2) and (3) hold here as in the last case, and the values of α, β, γ given in (5) remain the same. The driving-surface is, however, different, being traced out by a straight line which always remains parallel to the plane of xy, meets the helix described by P, and touches the cylinder whose radius is $= r\cos\frac{\pi}{n}$ (see Fig. 3, where PA represents the generating line drawn from a point P of the helix to touch the cylinder BC). Now the equations to the helix being

$$x = r\cos\phi, \quad y = r\sin\phi, \quad z = kr\phi \quad . \quad . \quad . \quad (17)$$

while that to the cylinder is

$$x^2+y^2 = \left(r\,.\,\cos\frac{\pi}{n}\right)^2 = r_1^{\,2} \quad . \quad . \quad . \quad (18)$$

suppose, if we draw from the point P (xyz) of the helix a tangent in the

plane $z=kr\phi$ to (18), the co-ordinates of the point of contact (see Fig. 3) will be

$$\left.\begin{aligned} x_1 &= r_1 . \cos\left(\phi - \frac{\pi}{n}\right) \\ y_1 &= r_1 . \sin\left(\phi - \frac{\pi}{n}\right) \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (19)$$

Now the equation to the tangent drawn through the point $x_1 y_1$ of the circle $x^2+y^2=r_1^2$ is

$$xx_1+yy_1=r_1^2 \quad . \quad . \quad . \quad . \quad (20)$$

And substituting in this equation the values of x_1 and y_1 derived from (19), we obtain as the equations of the generator,

$$xr_1 . \cos\left(\phi - \frac{\pi}{n}\right)+yr_1 . \sin\left(\phi - \frac{\pi}{n}\right) = r_1^2, \quad z = kr\phi \quad . \quad (21)$$

and as the equation to the driving-surface,

$$x . \cos\left(\frac{z}{kr} - \frac{\pi}{n}\right) + y . \sin\left(\frac{z}{kr} - \frac{\pi}{n}\right) = r \cos\frac{\pi}{n} \quad . \quad (22)$$

Now

$$\left(\frac{dF}{dx}\right) = \cos\left(\frac{z}{kr} - \frac{\pi}{n}\right), \quad \left(\frac{dF}{dy}\right) = \sin\left(\frac{z}{kr} - \frac{\pi}{n}\right)$$

$$\left(\frac{dF}{dz}\right) = \frac{1}{k}\left\{\frac{y}{r} . \cos\left(\frac{z}{kr} - \frac{\pi}{n}\right) - \frac{x}{r} . \sin\left(\frac{z}{kr} - \frac{\pi}{n}\right)\right\}$$

or, since P (xyz) is a point at once in the helix and the skew surface,

$$\left(\frac{dF}{dz}\right) = \frac{1}{k} . \sin\frac{\pi}{n}$$

Also

$$\left\{\left(\frac{dF}{dx}\right)^2 + \left(\frac{dF}{dy}\right)^2 + \left(\frac{dF}{dz}\right)^2\right\}^{\frac{1}{2}} = \frac{1}{k}\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}$$

And substituting those values of $\left(\frac{dF}{dx}\right)$, etc., in (8), we have for the direction cosines at the point P,

$$\left.\begin{aligned} \cos\lambda &= -\frac{k . \cos\left(\frac{z}{kr} - \frac{\pi}{n}\right)}{\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}} \\ \cos\mu &= -\frac{k . \sin\left(\frac{z}{kr} - \frac{\pi}{n}\right)}{\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}} \\ \cos\nu &= -\frac{\sin\frac{\pi}{n}}{\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}} \end{aligned}\right\} \quad . \quad . \quad (23)$$

And putting the values of $\alpha, \beta, \lambda, \gamma, \mu, \nu$ in the equations of motion (2) and (3), we have

$$M \cdot \frac{d^2z}{dt^2} = G - R\left\{\frac{\mu_1 k}{\sqrt{1+k^2}} + \frac{\sin\frac{\pi}{n}}{\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}}\right\} \quad . \quad (24)$$

$$\begin{aligned} \frac{d^2\phi}{dt^2} &= \frac{Rr}{M\rho^2} \cdot \left\{ \left\{\frac{k\cos\left(\frac{z}{kn} - \frac{\pi}{n}\right)}{\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}} - \frac{\mu_1 \sin\frac{z}{kr}}{\sqrt{1+k^2}}\right\}\sin\frac{z}{kr} \right. \\ &\quad \left. - \left\{\frac{\mu_1 \cdot \cos\frac{z}{kr}}{\sqrt{1+k^2}} + \frac{k \cdot \sin\left(\frac{z}{kr} - \frac{\pi}{n}\right)}{\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}}\right\}\cos\frac{z}{kr} \right\} \\ &= \frac{Rr}{M\rho^2} \cdot \left\{\frac{k \cdot \sin\frac{\pi}{n}}{\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}} - \frac{\mu_1}{\sqrt{1+k^2}}\right\} \end{aligned} \quad . \quad (25)$$

Hence

$$R = \frac{M \cdot \rho^2}{r \cdot \left\{\frac{k \cdot \sin\frac{\pi}{n}}{\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}} - \frac{\mu}{\sqrt{1+k^2}}\right\}} \cdot \frac{d^2\phi}{dt^2}$$

But

$$\frac{d^2\phi}{dt^2} = \frac{\pi r}{h} \cdot \frac{d^2z}{dt^2}$$

and making the necessary substitutions, we obtain for the ratio between the forces producing rotation and translation,

$$\frac{R}{G} = \frac{2\pi\rho^2}{\frac{\mu_1}{\sqrt{1+k^2}}(2\pi\rho^2 k - rh) + \frac{\sin\frac{\pi}{n}}{\sqrt{k^2 + \left(\sin\frac{\pi}{n}\right)^2}}\left(2\pi\rho^2 \sin\frac{\pi}{n} + rhk\right)} \quad (26)$$

In precisely the same manner as in the former case, and on the same hypotheses, we may show that if G″ denote the gaseous pressure in a bore rifled on the system we are now considering, and

G denote the gaseous pressure in a similar smooth-bored gun, we shall have

$$G'' = G + R\left\{\frac{\mu_1 k}{\sqrt{1+k^2}} + \frac{\sin\frac{\pi}{n}}{\sqrt{k^2+\left(\sin\frac{\pi}{n}\right)^2}}\right\} \quad . \quad . \quad (27)$$

Hence if we have three guns of the same diameter of bore, viz., a smooth-bore gun; a rifled gun, the grooves of which are similar to those shown in Fig. 1; and a third, rifled polygonally; and if we suppose that the shot in each case are of the same weight, and, further, that in each case the velocity-increments at the moment under consideration are equal, then the pressures upon the base of the shot will be as follow:—In the case of the

$$\left.\begin{array}{l} \text{Smooth-bored gun, pressure} = G \\ \text{First rifled gun, pressure} = G + \dfrac{R}{\sqrt{1+k^2}}(\mu_1 k + 1) \\ \text{Polygonally-rifled gun, pressure} \\ \qquad = G + R\left\{\dfrac{\mu_1 k}{\sqrt{1+k^2}} + \dfrac{\sin\frac{\pi}{n}}{\sqrt{k^2+\left(\sin\frac{\pi}{n}\right)^2}}\right\} \end{array}\right\} \quad (28)$$

We shall now give examples of the cases we have been discussing to exhibit numerically the above results.

Let us suppose that two 7-inch guns are rifled—the first according to the method shown in Fig. 1, with a pitch of one turn in 294 inches, the other octagonally, with a pitch of one turn in 130 inches. It is required to determine in each case the pressure on the driving-surface in terms of the pressure on the base of the shot. Now, in the first case, from (13),

$$\text{Pressure on driving-surface} = \frac{2\pi\rho^2\sqrt{1+k^2}}{hr(k-\mu_1)+2\pi\rho^2(\mu_1 k+1)} \cdot G$$

where

$$\pi = 3{\cdot}14159,\ \rho = r\sqrt{\tfrac{1}{2}} = 2{\cdot}475,\ k = 13{\cdot}3697,\ h = 294,\ r = 3{\cdot}5,\ \mu_1 = {\cdot}1666$$

whence we obtain

$$R = {\cdot}0375\,G \quad . \quad . \quad . \quad . \quad . \quad (29)$$

In the second case, from (26),

Pressure

$$= \frac{2\pi\rho^2}{\dfrac{\mu_1}{\sqrt{1+k^2}}(2\pi\rho^2 k - rh) + \dfrac{\sin\pi}{\sqrt{k^2+\left(\sin\frac{\pi}{n}\right)^2}}\left(2\pi\rho^2\sin\frac{\pi}{n} + rhk\right)} \cdot G$$

where

$$\pi = 3{\cdot}14159$$

$$\rho = \frac{1}{12} c^2 \cdot \frac{2 + \cos \frac{2\pi}{n}}{1 - \cos \frac{2\pi}{n}} = 2{\cdot}350 \text{ (c = length of side of polygon)}$$

$$k = 5{\cdot}9117, \quad h = 130, \quad r = 3{\cdot}5, \quad n = 8, \quad \mu_1 = {\cdot}1666, \quad \frac{\pi}{n} = 22^\circ\ 30''$$

$$\text{whence} \qquad R = {\cdot}1706\ G \quad . \quad . \quad . \quad . \quad (30)$$

That is, on the supposition of the same pressure on the base of the shot, the pressure on the driving-surface is in the latter case nearly five times as great as in the former, and is, in fact, no inconsiderable fraction of the propelling force.

Let us now compare the gaseous pressures on the base of shot of the same weight supposed to be fired from the guns above described, and from a smooth-bored gun. From Equations (28) we have the pressure upon base of shot fired from

Smooth-bored gun	= G
First rifled gun	= 1·009 G
Polygonal gun	= 1·041 G

In these calculations we have taken the coefficient of friction $= \frac{1}{6}$. It is necessary, however, to observe that very little is known concerning the value of this constant at pressures so high as those with which we have here to do. It is evident that in the case of the contact of similar metals, when the point of seizure is approached, the coefficient of friction cannot be considered independent of pressure; and it is probable that when the rubbing surfaces of both projectile and groove (or other driving-surface) are of the same hard material, the coefficient of friction may be occasionally enormously increased.

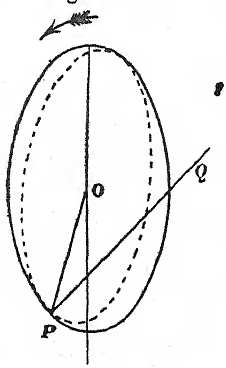
The resistance due to this cause might under certain circumstances be sufficient to ensure the destruction of the gun; and this view is to some extent corroborated by the occasional bursting of guns, the failure of which it is difficult to attribute to any other cause; and in the instances referred to, the recovered fragments of the shot were thought to exhibit decided appearances of seizure.

If in Equation (26) we substitute δ for $\frac{\pi}{n}$, we shall have

$$\frac{R}{G} = \frac{2\pi\rho^2}{\frac{\mu_1}{\sqrt{1+k^2}}(2\pi\rho^2 k - rh) + \frac{\sin\delta}{\sqrt{k^2 + (\sin\delta)^2}}(2\pi\rho^2 \sin\delta + rhk)} \qquad (31)$$

And this equation will represent the ratio of the pressures R and G in any system of rifling, δ being the angle which the radius makes with the normal to the driving-surface. Thus in an elliptically-bored gun (see Fig. 4) the angle OPQ represents the angle δ, and we obtain $\frac{R}{G}$ by substituting in (31) the value of this angle; by putting $\delta = 90°$, we may derive Equation (13) directly from (31).

Fig. 4.



We have not in this note entered into the question of the absolute pressures existing in the bores of ordnance of various natures, as the subject is too extensive and of too great importance to be disposed of within the limits of a short paper.

Artillerists acquainted with the subject will be able to form rough approximations to these pressures from the experiments made abroad with smooth-bored guns, with a view to the elucidation of this important question. It is much to be regretted that no experiments of the nature referred to have been attempted in England under Government auspices, as they are of a description which precludes their being satisfactorily made by private individuals, and as the information to be derived from them would be especially important in the case of rifled cannon, where so many new conditions are introduced into the problem as to render previous investigations of but little value.

We shall, however, in a future note endeavour to discuss this subject, making use of the data at our disposal.

IV.

ON THE TENSION OF FIRED GUNPOWDER.

(*Transactions of the Royal Institution,* 1871.)

BEFORE entering on the investigations which will be the chief subject of my discourse this evening, I find it necessary to give a sketch of the means that have hitherto been adopted to determine, and the views that have been entertained concerning, the pressure of fired gunpowder.

The first attempt made to explain the action of gunpowder was, I believe, that of M. de la Hire, who, in the History of the French Academy for 1702, ascribed the force of fired gunpowder to the behaviour of the air enclosed in and between the grains of powder. This air he considered to be highly heated by the combustion of the charge, and the consequent elasticity to be the moving force of the projectile. Robins, who followed M. de la Hire as the next writer on the subject, and who may be considered to have laid the foundation of this, as of so many other departments of artillery science, points out how inadequate to the effect are the forces supposed to act by M. de la Hire.

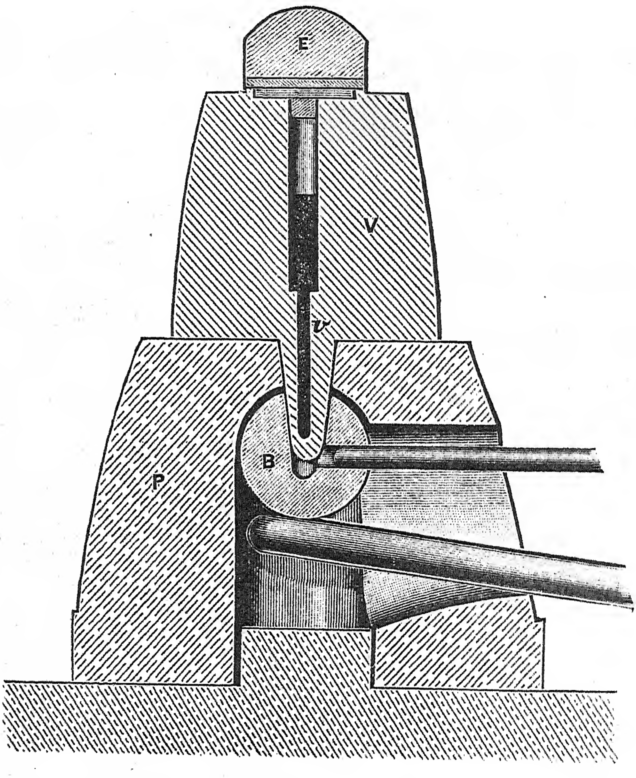
He himself instituted a carefully-planned and well-conducted series of experiments, in which he determined the quantity of permanent gas generated by the explosion of gunpowder; adduced experiments which he considered to prove that this quantity is the same whether the powder be exploded in the air or in vacuo; and finally determined the increase of elasticity due to the supposed temperature of the explosion.

The conclusions at which Robins arrived were briefly as follow: —1. That the whole action of the powder on the projectile was due to the permanent gases generated by the explosion. 2. That at ordinary temperature and atmospheric pressure the permanent gases occupied about 240 times the volume of the unexploded powder.

3. That the heat of combustion increased this volume to about 1000 times that of the powder, and that hence the maximum force of gunpowder—somewhat less with small, somewhat greater with large charges—was about 1000 atmospheres, that is to say, about $6\frac{1}{2}$ tons on the square inch.

But although Robins considered this pressure the maximum exerted by fired gunpowder, it is worthy of remark that he recognised

FIG. 1.



the intensity of the local pressure which arises when the gases generated have space sufficient to acquire a considerable velocity before meeting with an obstacle. In a common musket he placed a bullet 16 inches from the charge, and found that at the seat of the shot the barrel was bulged like a bladder to twice its original diameter, while two pieces were blown out of it.

But the first regular experiments which had for object the determination of the pressure of gunpowder fired in a close vessel or

chamber were those of Count Rumford, made in 1793, and published in the *Transactions of the Royal Society* for 1797.

The apparatus used by Count Rumford is figured in this diagram (Fig. 1), and will be readily understood. V is a small but strong wrought-iron vessel resting on the pedestal P, and having a bore of $\frac{1}{4}$-inch diameter. The bore is closed by the hemisphere E, upon which any requisite weight may be placed. There is a closed vent, v, which is filled with powder, and the charge is fired by means of a red-hot ball, B.

The *modus operandi* was as follows:—A given charge being placed in the bore, a weight which was considered equivalent to the gaseous pressure was applied on E. If the charge of powder lifted the weight and let the gases escape, the weight was increased until it was just sufficient to confine it, and the pressure represented by the weight was assumed to be that of the powder.

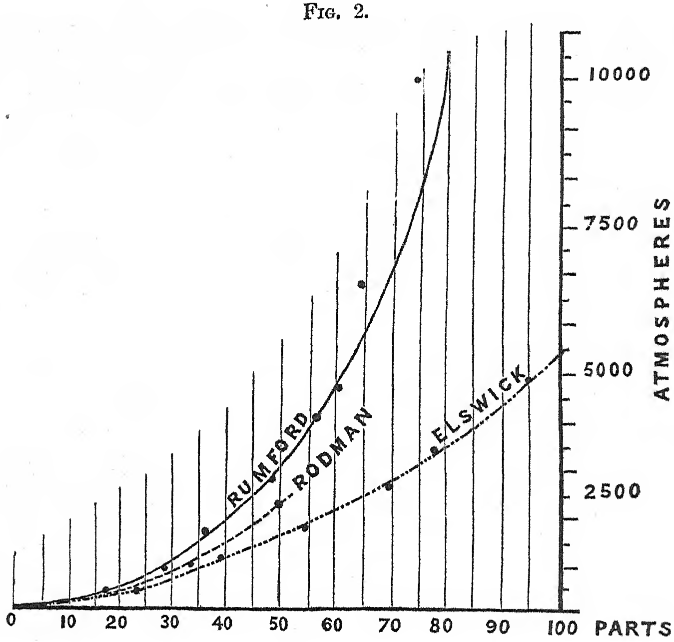
The powder used was sporting, of very fine grain, and it is to be remarked that its composition, there being only 67 per cent. of saltpetre, differed notably from ordinary powder. The charges used, moreover, were very small, the maximum being only 18 grains. In one case, indeed, the vessel was filled: about 28 grains were necessary to fill the chamber; but by this experiment the vessel was destroyed. The objects Rumford had in view were—first, to ascertain the limit of the force exerted by the exploded powder when the gases are at their maximum density; secondly, to determine the relation between the density of the gases and the tension.

The curve shown here (Fig. 2) exhibits the results of the first and most reliable series of Rumford's experiments, and you will observe how nearly, up to charges of 15 grains (60 per cent.), the curve, which is expressible by the empirical equation $y=x^{1+\cdot 0004x}$, passes through the observed points. Were this law assumed to be true up to the point of maximum density,* it would give the maximum tension at about 29,000 atmospheres, or 191 tons on the square inch. But, great as this pressure is, Count Rumford considers it much below the truth. In addition to the experiments graphically represented by the diagram to which I have drawn your attention, Count Rumford made a second series, the results of which, to use his own words, "are still more various, extraordinary, and inexplicable." From this diagram you will observe that the tension of the gas in the first series of experiments was with 12 grains of powder about 2700 atmospheres; but in this second series the pressure with the

* Considered as unity.

same charge is repeatedly found to be above 9000 atmospheres. Count Rumford does not attempt to explain the enormous discrepancy between the two sets of experiments, unless a remark on the heat of the weather during the second set can be so considered; but, relying on this second series, and on the experiment in which the vessel was destroyed by 28 grains, Count Rumford arrives at the conclusion that 101,021 atmospheres, or 662 tons on the square inch, is the measure of the initial force of the elastic fluid generated by the combustion of gunpowder. Rumford meets the objection that, if the

Fig. 2.



tension were anything like that he names, no gun would have a chance of standing, by assuming that the combustion of the powder is much slower than is ordinarily supposed, and, indeed, lasts all the time the shot is in the bore; and he further accounts for the enormous initial tension by ascribing it to the elasticity of the aqueous vapour or steam contained in the powder. Supposing, from M. de Betancourt's experiments, that the elasticity of steam is doubled by every addition of temperature equal to 30° Fahr., his only difficulty, and one which he leaves to his successors to explain, is why the steam liberated by the combustion of the powder does not exercise a much higher pressure than the 100,000 atmospheres he has assigned to it.

In 1843 Colonel Cavalli proposed to insert in the bore of a gun a series of small barrels, intended to throw a wrought-iron spherical ball. By ascertaining the velocities of these balls Colonel Cavalli considered that he would be able to assign the corresponding pressures. Colonel Cavalli's plan was actually carried out, and from his experiments he deduced what ought to be the theoretical thickness of the metal at various points along the bore. But a very great improvement on Colonel Cavalli's method was introduced in 1854 by a Prussian Artillery Committee, under the direction of General (then Major) Neumann.

The plan adopted by the Prussian Committee was as follows:—

In, say, the centre, or any other point desired, of the powder chamber, a hole was drilled, and in this hole was fitted a small gun-barrel with a calibre of about $\frac{3}{10}$ of an inch and a length of, say, 8 inches. Now, suppose the gun to be loaded, and suppose further that in the small side gun we place a cylinder whose longitudinal section is the same as that of the projectile. On the assumption that the pressure throughout the powder chamber is uniform, the cylinder and the projectile will in equal times describe equal spaces, and after the cylinder has travelled 8 inches it will be withdrawn from the action of the gas. If, then, we ascertain the velocity of the cylinder, we shall know that of the projectile when it has described in the bore a space of 8 inches. Again, if we make the section of the cylinder half that of the projectile, it will describe in the same time double the space, and will have acquired double the velocity, and so on; so that, for example, if the section of the cylinder be one-eighth that of the projectile, and we ascertain the cylinder's velocity, we know the velocity of the projectile after it has described 1 inch.

These Prussian experiments do not, however, despite the ingenuity of their method, possess a very high interest to us, as they were applied only to comparatively very small guns, the 6-pr. and 12-pr. smooth-bores, and had for their chief object the comparison between elongated and non-elongated cartridges.

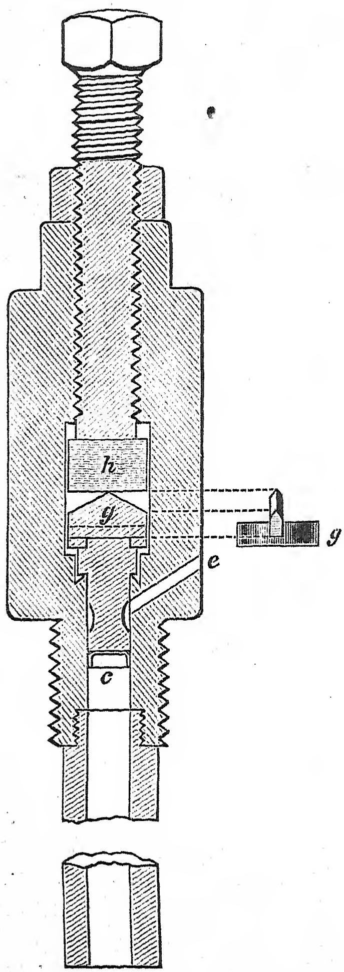
Further on I shall advert to reasons which prevent this method being altogether reliable, especially for large guns; but I may state that the general result seems to have been that in the 6-pr. the maximum pressure was about 1100 atmospheres, while in the 12-pr. it was nearly 1300 atmospheres.

I shall also further on advert to another remarkable observation made by the Prussian Committee—namely, that in every charge

with which they experimented two maxima of tension were distinctly perceptible.

The distinguished Russian artillerist, General Mayevski, who has written an elaborate memoir on the pressure in the bores of guns, founded on these experiments, confirms the results at which the Prussian Committee have arrived, and points out that from the experiments the maximum pressure must be attained before the bullet is any considerable distance from its initial position.

Fig. 3.



General Neumann's method appears to have been repeated in Belgium about the year 1860 with a 70-pr. rifled gun. I have not seen a detailed report of these trials, but the maximum pressure with ordinary powder was stated to be about 3000 atmospheres, or nearly 20 tons per square inch.

In 1857-8-9 Major Rodman carried on for the United States a most interesting and extensive series of experiments on gunpowder.

The celebrity to which Major Rodman's ingenious instrument has attained, the great use which has been made of it in Europe, and the fact that he appears to have been the first person who experimented on the effect of size of grain, and proposed prismatic powder, oblige me to describe both his instrument and his experiments in some detail.

It is most unfortunate that experiments so well devised, and carried out with so much care, should be rendered in many cases almost valueless by the absence of important data, by the admission of manifestly erroneous observations, and, finally, by results passed over in silence which are not only frequently anomalous, but in some cases absolutely impossible.

The instrument which Major Rodman devised is shown in this drawing (Fig. 3). Suppose we wish to determine the pressure in the chamber of a gun. A hole is drilled into it, and a cylinder with a small passage down its centre is inserted. To this cylinder is fitted the indicating apparatus, which consists of the indenting tool *g*, carrying a knife, shown in elevation and section. Against the knife is screwed a piece of soft copper, *h*. You will have no difficulty in understanding the action of this apparatus. The pressure of the gas acting on the base of the indenting tool causes a cut in the copper, and by mechanical means the magnitude of the force capable of producing a similar cut can be determined. A small cup at *c* prevents any gas passing the indenting tool, and the channel *e* provides for the escape of gas, should any pass on account of defective arrangements.

Major Rodman's first series of experiments of importance was the determination of the pressure at different points of a 42-pr. smooth-bored gun, two descriptions of cartridges being used—one being made up with 10 lbs. of ordinary grained powder, the other being what he terms an accelerating cartridge of 13 lbs., a description of which is not given.

Major Rodman gives the mean results of this series in a tabulated form, but I have transferred his results to this diagram (Fig. 4), and I draw your especial attention to them. You will notice that among the observed points I have drawn in each case a curve representing, as nearly as may be, the observations. Remark how widely the two curves differ. The horizontal line, the axis of abscissæ, represents the length of the bore, and by the length of the ordinates is indicated the maximum amount of pressure existing at any particular point of the bore.

These curves illustrate also another point. Since the ordinates represent the pressures, and the abscissæ the travel of the shot along the bore, the areas, that is to say, the spaces between the curves and the axis of abscissæ, represent the total work done on the shot by each of the charges experimented with. Your eye will tell you that the area, that is the work done on the shot, is, in the case of the grained, nearly double its amount in that of the accelerating cartridge, but the actual work in each case was known to be nearly identical.

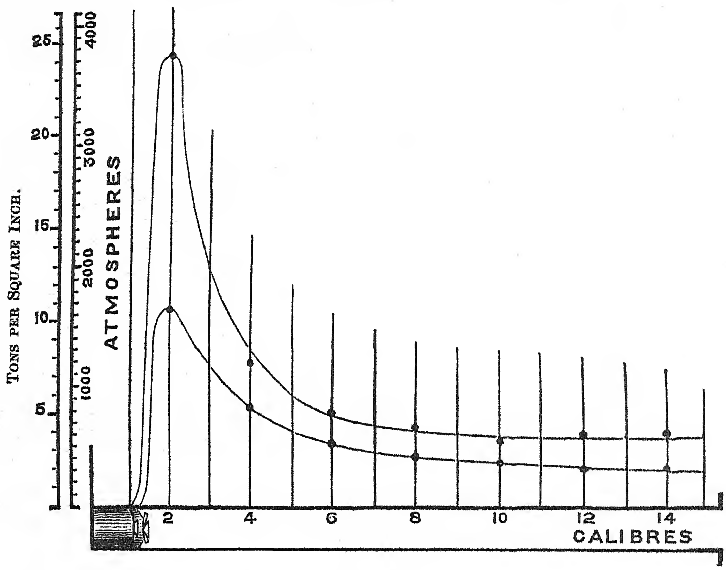
There is here, therefore, a grave contradiction, which requires explanation. But we have not done yet. Knowing, as we do from these curves, the amount of the work done by each nature of

cartridge on the shot, we are in a position to compute the velocity with which the shot would quit the bore.

Performing this calculation, we find that the lesser area represents a muzzle velocity of about 1950 feet, while the larger one represents a muzzle velocity of about 2620 feet—results differing widely from the truth, and showing that the larger of the two areas is about three times greater than it should be, while even the smaller is at least 50 per cent. too high.

Two interesting series were fired from the same gun to determine the pressure on the bottom of the bore when the weight of the charge

Fig. 4.



was varied, that of the shot remaining constant, and when the weight of the shot was varied, the charge remaining constant.

As far as the experiments were carried, the pressure in both cases appeared to be nearly directly proportional—in the one instance to the weight of the shot, in the other to the weight of the charge.

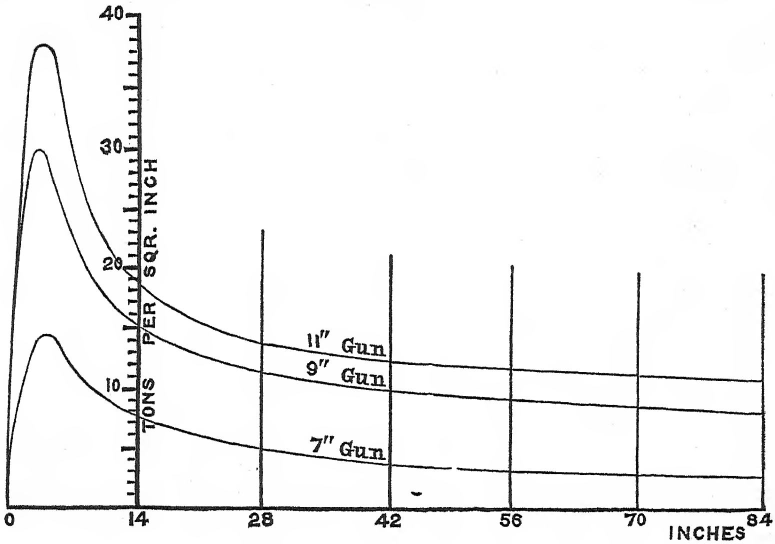
Experiments were then made to determine the pressures in guns of 7-inch, 9-inch, and 11-inch bore, and were so arranged that in each gun an equal column of powder (that is, an equal weight of charge) was behind an equal column or weight of shot. It is hardly necessary to point out that in each gun, in the motion of the shot along the bore, at every point, the gases would be equally expanded, and any incre-

ment of pressure in the larger-bored guns would be attributable to the use of the larger charge.

The mean result of these experiments is given in this diagram (Fig. 5). As before, there are many anomalies and contradictions in the experiments themselves. You will observe what a great increase of pressure is credited to the larger guns, although the same column of powder and shot exists in all cases. As before, again the work done on the shot as indicated by these areas is enormously too large.

The results given by these experiments are the more curious,

Fig. 5.



because, as Major Rodman himself points out, they are entirely at variance with some subsequent experiments, in which charges of powder of various weights, from 1700 to 11,000 grs., occupying always one-fourth of the space in which they were fired, and the charge escaping through the vent, gave pressures practically identical.

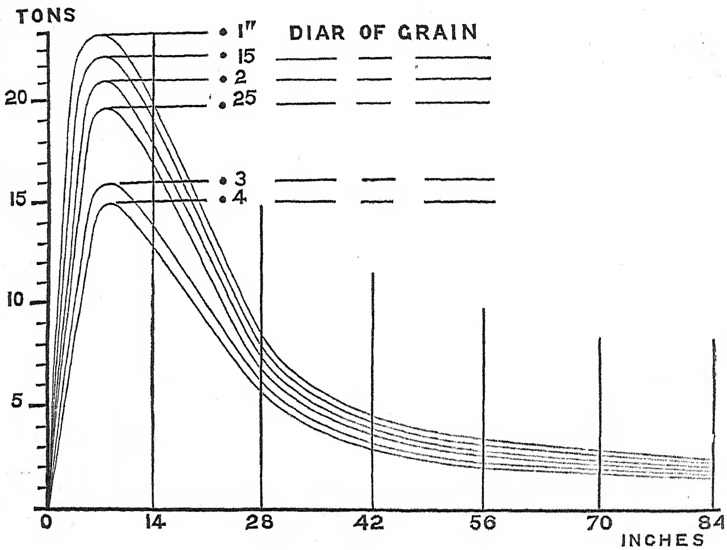
The effect of the size of the grains was the next subject investigated. The comparative results (care still being taken not to accept these areas as representing the work done on the shot) are obvious from a glance at Fig. 6; and Major Rodman arrives at the conclusion that the velocities due to our present charges of small-grained powder may be obtained with a greatly diminished strain on the gun by the

use of powder properly adapted in size of grain to the calibre and length of bore with which it is to be used.

With this statement I entirely agree, and can only regret that, from the absence of information as to density and other particulars of the various samples of powder used, these particular experiments have been of no use to us in this country for comparative purposes.

The only other experiments of Major Rodman to which I shall draw your attention belong to a series which I am able to compare with the experiments of Count Rumford, as to the pressure of fired

Fig. 6.



gunpowder in various degrees of expansion—that is, the unfired powder occupying a definite proportion of the space in which it is exploded. Fig. 7 is a drawing of the apparatus Major Rodman used. You will observe that in this apparatus the fired charge escapes through the vent, while in Count Rumford's experiments the products of explosion were generally more or less confined.

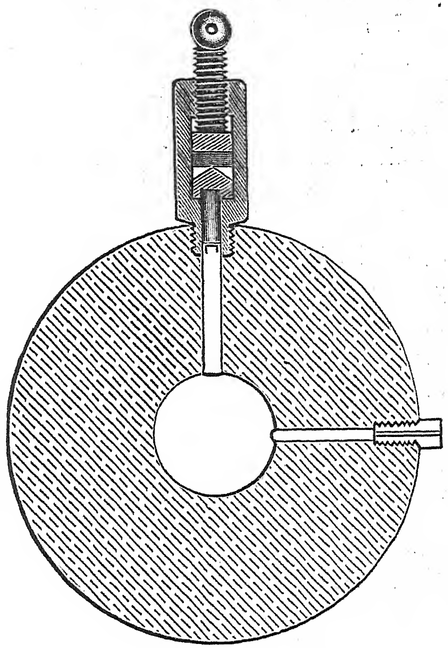
On the other hand, Count Rumford's charges were exceedingly minute, while the charges we are now considering ranged from 700 to 7000 grs.

On the same diagram (Fig. 2) upon which I placed Count Rumford's results I have placed Major Rodman's. You will perceive the difference between them. But Major Rodman's experi-

ments have not been carried far enough to possess for us much interest.

Major Rodman, like Count Rumford, endeavoured to ascertain the maximum force which powder was capable of exerting when fired in its own volume. Major Rodman fired various charges in enormously strong shells, through a small vent $\frac{1}{10}$ inch in diameter. He considered, from some experiments with which I need not trouble you, that in all cases the maximum pressure would be exerted before the shell burst. His results, however, were very diverse, varying from 32 tons per square inch (4900 atmospheres) to 82 tons, or about 12,400 atmospheres, and, singularly enough, the highest pressure was given by the smallest charge; from the great discrepancies, as well as from other considerations, I do not think we can accept these determinations as entitled to much weight.

FIG. 7.



Bunsen and Schischkoff's experiments, both from their completeness, and the eminent position of the distinguished chemists who conducted them, may justly rank among the most important which have been made on our subject.

They were directed, in the first place, to determine the exact nature, both of the permanent gases and the solid products generated by the explosion of powder; secondly, to determine the heat generated by the act of explosion; thirdly, to determine the maximum pressure which gunpowder fired in a close chamber would give rise to; and, finally, to determine the total quantity of work which a given weight of gunpowder is capable of producing.

The apparatus adopted for obtaining the products of combustion was so arranged that the powder to be analysed falls in a very finely-divided stream into a heated bulb, in which, and in

tubes connected with it, the resulting products are collected for examination.

MM. Bunsen and Schischkoff, in drawing attention to their results, and the extraordinary difference between their estimates and those given by so eminent an authority as Piobert, point out that many of the assumptions previously made must depend on very faulty premises; but their own experiments have not altogether escaped attack, and I think we are bound to receive some of their results with great reservation, until it can be demonstrated that the products of combustion are the same in the bore of a gun as when produced in the method followed in these experiments.

I shall not detain you with the results of their analysis, which you see, however, in this table,* and shall only point out that the permanent gases at a temperature of 0° C. and pressure of 760 mm. occupied a volume 193 times greater than that occupied by the powder, and represented about $\frac{31}{100}$ the weight of the powder. The remainder was solid residue, and MM. Bunsen and Schischkoff conceive that, although a portion of these solid matters may undoubtedly be volatilised by the high temperature of the explosion, yet any pressure which may be exerted by such vapours is quite insignificant. This opinion appears to be founded on the fact that the solid residue arising from the explosion of gunpowder is not fused when exposed to the action of a jet of inflamed hydrogen.

Piobert and other authorities, on the other hand, consider that the pressure exerted by the volatilised residue has far more influence on the pressure than the permanent gases.

* Transformation experienced by gunpowder in burning, after Bunsen and Schischkoff.

1 grm. powder		
Nitre		0·7899
Sulphur		0·0984
Charcoal	C	0·0769
	H	0·0041
	O	0·0307

Gave when exploded

			grm.	c.c.
Residue	grm. 0·6806	$KOSO_3$	0·4227	
		$KOCO_2$	0·1264	
		KOS_2O_2	0·0327	
		KS	0·0213	
		KC_yS_2	0·0030	
		$KONO_5$	0·0372	
		C	0·0073	
		S	0·0014	
		$2NH_4O,3CO_2$	0·0286	
Gases	grm. 0·3138	N	0·0998	= 79·40
		CO_2	0·2012	= 101·71
	0·9944	CO	0·0094	= 7·49
		H	0·0002	= 2·34
		HS	0·0018	= 1·16
		O	0·0014	= 1·00
				193·10

The temperature of the fired gunpowder was determined by exploding a small charge of powder enclosed in a tube, which was itself immersed in a larger tube containing water. From the increment of temperature communicated to the water by the explosion, it was found that one part of fired powder would raise 620 parts of water by 1° Cent., and hence it was calculated that the temperature of gunpowder fired in a close chamber impervious to heat is 3340° Cent., or 5980° Fahr.

Assuming, first, that the products obtained in the two methods I have just described are identical, and, secondly, that no variations in the products arise from the combustion of large charges, this result would be very near the truth.

The pressure in a closed vessel is readily deducible from the above data, and MM. Bunsen and Schischkoff compute that the maximum tension which the gas can attain—to which it may approximate, but can never reach—is about 4374 atmospheres, or about 29 tons on the square inch.

I shall shortly have occasion to show that this pressure has been undoubtedly reached in the case of heavy guns, and considerably exceeded in the case of powder fired in closed vessels. MM. Bunsen and Schischkoff also compute, from their data, the theoretical work of a kilog. of gunpowder at 67,400 kilogrammetres, that is 67,400 kilogs. raised 1 metre in height. The Committee on explosives have, however, realised in the shot alone nearly 60,000 kilogrammetres per kilog. of powder in a comparatively short gun; and it may therefore be conjectured that this estimate, like that of the maximum pressure, is considerably too low, although undoubtedly much nearer the truth than the extravagant estimates which have frequently been made.

In the year 1861-2 Sir W. Armstrong, in conjunction with myself, made several experiments to determine the maximum pressure of powder in the bores of what were then considered very large guns —the 110- and the 70-prs. Two methods were adopted, and although they, like nearly every experiment connected with gunpowder, gave results in some degree anomalous, yet the conclusion at which we arrived—namely, that the maximum pressure with the powder then used, in the bores of the guns I have mentioned, was about 17 tons on the square inch—is probably not very far removed from the truth.

The first of these methods consisted of an arrangement carried in the nose or front part of the projectile, and is shown in these

drawings (Figs. 8 and 9). The apparatus itself consisted of a case containing seven little cells, *bb*. Each of these cells contained a small pellet, *a*, of the same weight, and each of these pellets is retained in the front portion of the cell by means of a small wire.

FIG. 8.

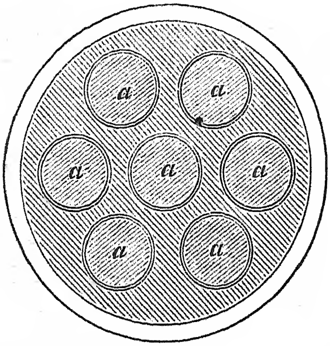
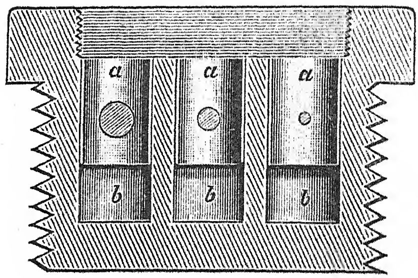
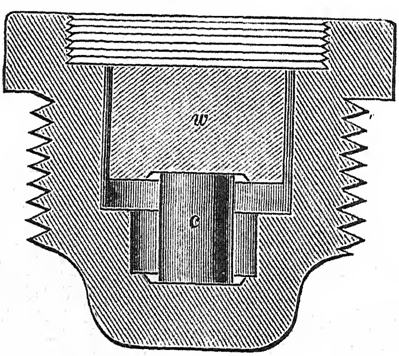


FIG. 9.



Experiments were then carefully made to ascertain the exact pressures that a graduated series of wires would carry. You will now readily understand this method of deducing the maximum pressure. If we know the maximum pressure exerted during the passage of the shot through the bore to give motion to any known portion of the shot's weight, we can deduce the pressure acting on the whole shot itself. By properly adjusting the strength of the wires, we found that certain wires would give motion to the pellets without shearing; others would not. Hence we deduced an approximate maximum pressure.

FIG. 10.



The other arrangement was also carried in the front of the projectile, and is here shown (Fig. 10). In this case a known weight *w* is supported, or rather has motion communicated to it, by means of a cylinder of soft metal *c*. The amount of crush on the cylinder serves as an indication of the force to which it has been subjected.

It is not possible in anything like a reasonable time to give an analysis of the voluminous investigations of Piobert on the question of gunpowder.

Generally, however, his views seem to be that he ascribes much of the initial pressure of gunpowder to the effects of the vaporised solid products increasing enormously the tension due to the permanent gases.

He points out errors in some of Rumford's conclusions, but accepts as tolerably accurate the pressures given by Rumford's first series, which would, at maximum density, give a tension of about 29,000 atmospheres.

I have now run over hastily, but I hope intelligibly, the principal experiments which have been made and the views which have been entertained on the subject of the pressure of fired gunpowder. The enormous discrepancies between the 1000 atmospheres estimated by Robins and the 100,000 atmospheres of Rumford will not have escaped you; and even coming to quite recent dates, the difference of opinion between authorities like Piobert on the one hand, and Bunsen and Schischkoff on the other, are quite startling enough to show you the difficulties with which the subject is enveloped. What I now have to detail to you chiefly relates to the labours of a Committee, under the presidency of Colonel Younghusband, recently appointed to examine into our gunpowder, which has for some years enjoyed on the Continent the unenviable denomination of "brutal powder."

The researches of this Committee having been devoted in the first place to a special object—the production of a powder suitable for the very large guns which are now required by the services—all the experiments hitherto made have been undertaken with this sole end in view. We have turned so far neither to the right hand nor the left, and in consequence our knowledge relating to many important points is very incomplete, in others altogether defective; but, as far as my time permits, I shall lay a few of our facts before you as concisely as I can, and where I may venture to theorise I shall only give views which I believe to be shared in common with myself by the distinguished gentlemen with whom I have the honour of being associated.

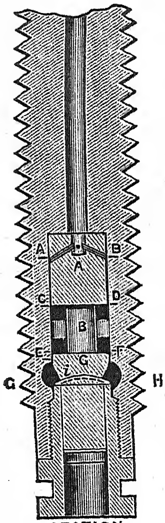
The guns we have principally used have been three in number—a gun of 2·1-inch diameter, firing projectiles of 4¾ lbs., and charges of 9 ozs.; an 8-inch gun, firing projectiles of 180 lbs., and charges of from 20 to 40 lbs.; and a 10-inch gun, firing projectiles of 400 lbs., and charges of from 60 to 70 lbs. of powder.

The means we have used to determine the pressure have been likewise three—first, a Rodman gauge; secondly, a crusher gauge,

designed to overcome certain faults in the Rodman gauge, which I shall presently describe; thirdly, a chronoscope, designed for measuring very minute intervals of time.

The Rodman gauge I have already fully described. The crusher gauge is shown in this drawing (Fig. 11), and consists of a screw plug of steel let into the gun at any desired point, which admits of a cylinder of copper, B, being placed in the chamber CDEF.

Fig. 11.



SECTION

The entrance to this chamber is closed by the movable piston C, as in the case of the Rodman gauge, and the admission of gas is prevented by the use of a gas check.

You will have no difficulty in understanding the manner in which results are arrived at with this instrument. When the gun is fired, the gas acts upon the base of the piston and compresses the copper cylinder. The amount of crush on the copper serves as an index to the maximum force exerted at that part of the bore where the plug is placed.

The chronoscope used by the Committee is delineated in Plates VI. and VII., p. 86. It consists of a series of thin discs, AA, each 36 inches in circumference, fixed at intervals on a horizontal shaft, and driven at a high speed by the heavy descending weight B, which is, during the experiment, continually wound up by the handle H, and with a little practice the instrument can be made to travel either quite uniformly or at a rate very slowly increasing or decreasing.

The precise rate of the discs is ascertained by means of the stop-clock * D, which can be connected or disconnected with the revolving shaft E at pleasure.

The speed with which the circumferences of the discs travel is in this instrument generally about 1200 inches per second. An inch therefore represents the 1200th part of a second, and as by means of a vernier we are able to divide the inch into 1000 parts, the instrument is capable of recording less than the one-millionth part of a second. I may mention, by way of enabling you to realise the extreme minuteness of this portion of time, that the millionth part of a second is about the same fraction of a second that a second is of a fortnight.

* An improved arrangement for registering the speed was afterwards introduced.

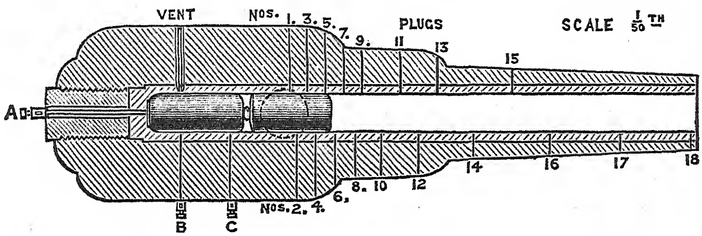
I shall now endeavour to describe to you how the shot marks on the instrument the record of its passage through the bore.

I need hardly remind most of you that when the primary of an induction coil is suddenly severed, a spark under proper management is given off from the secondary, and in the arrangement I am describing, the severance of the primary is caused by the shot in its passage through the bore, and the record of its passage is transferred to the discs in the following way.

The peripheries of the revolving discs are covered with strips of white paper coated with lampblack, and are connected with one of the secondary wires of an induction coil. The other secondary wire, carefully insulated, is brought to one of these dischargers, Y, opposite to the edge of a disc, and fitted so as to be just clear of it.

The mode of connecting the primary wires of the induction coils with the bore of a gun in such a manner that the shot in passing a

Fig. 12.



definite point shall sever the primary current, and thereby produce a spark from the secondary, is shown in Fig. 12 which represents a longitudinal section of the bore along which the shot is moving.

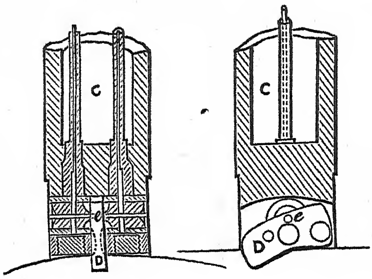
A hollow plug, C (see Fig. 13, p. 70), is screwed into the gun, carrying at the end next the bore a cutter, D, which projects slightly into the bore.

The cutter is held in this position by the primary wire, *e*, which passes in at one side of the plug, then through a hole in the cutter, and out at the other side of the plug.

When the shot passes the cutter it presses it level with the surface of the bore, thereby severing the primary and causing the induced spark to pass instantaneously from the discharger to the disc, making a minute perforation in the paper-covering upon the opposite part of the disc, and at the same time burning away the lampblack, so that the position of the perforation is marked by a white spot.

To prevent confusion, there is delineated in Plate VI., p. 86, only a single induction coil and cell; but you will understand that there is an induction coil for each disc, and that each disc, discharger, and coil form, so to speak, an independent instrument for recording the instant when the projectile passes a certain point in the bore of the gun.

Fig. 13.



It only remains to point out that before using the instrument, we must be satisfied that the various independent instruments of which I have spoken give corresponding results.

The best mode which occurred to us of doing this is to get a record upon each disc of the same event.

Thus it is obvious that if the whole of the primaries are cut simultaneously, the sparks on all the discs should be in a straight line, and the deviations from a straight line are the errors, either constant or variable, and from the observations the constant errors can, of course, be eliminated.

Two methods of securing a simultaneous rupture of the primaries have been followed. One plan consisted in wrapping all the wires round a small magazine of fulminate of mercury, and exploding the fulminate. The other consisted in collecting the whole of the wires on a small screen close to the muzzle of a rifle, and cutting them by means of a flat-headed bullet. Both methods have given excellent results.

Having now described the instruments, I turn to the guns. The arrangements in all the guns were similar in character, but I have given to you here (Fig. 12) a drawing of the 10-inch M. L. gun as representing the most perfect arrangement used in the early experiments. We have, in the first place, the power of firing the cartridges in different positions. Rodman's gauges, or the crusher gauges, are always placed in the holes marked ABC, and in such other holes as we may desire, while 8 holes every round are reserved for use with the chronoscope.

Suppose, for example, we wished to experiment with a charge of 70 lbs. of powder, our usual course would be: the chronoscope plugs would be placed alternately in the holes 4 to 11, and in 11 to 18, while the crusher gauges would be alternately in the holes ABC, 1, 14, 17, and in the holes ABC, 1, 4, 10.

The pressures derived from either the Rodman or the crusher gauge are read off from tables at once, but the determination of the pressure from the time curve given by the chronoscope is a very different matter.

I am aware that there are many authorities who consider it almost impossible to obtain from a time curve such as is given by the chronoscope reliable indications of the pressure, and I cannot wonder that many should so think.

We who have been investigating this subject, are quite alive to the fact that a cause of error far graver than any chronoscopic error lies in the difficulty, I might almost say impossibility, of assuring ourselves that the projectile in successive experiments should describe precisely the same space in passing between any two successive plugs; but, fortunately, errors of this description can generally be removed by known methods of interpolation and correction.

Again, if we relied for the determination of our maximum pressure on the observation of two velocities only at very short intervals, as trifling errors in the determination of the velocity would give rise to considerable variations in pressure, our results would be open to considerable doubt, but the fact is that, with the assumptions we are at liberty to make, I have found that it is not posssible materially to alter our pressure without setting our records altogether at nought.

The time curve—that is, the curve whose ordinate at any distance up the bore represents the time the shot has taken to arrive from zero at that spot—being drawn through the observed points, what may we assume respecting the curve representing the velocity? According to theory, we may assume that it commences by being convex to the axis of abscissæ, then becomes concave—that the radius of curvature becomes greater and greater as x increases, and, were the bore long enough, would be finally asymptotic to a line parallel to the axis of x.

Again, as regards the curve representing pressure. We know that the pressure will run up with extreme rapidity until it attains a maximum, and that after attaining a maximum the ordinates will rapidly decrease, the curve after passing the maximum being always convex to the axis of abscissæ.

These considerations, joined to the observations themselves, are amply sufficient to give us the information required. At the commencement of motion the plugs are very close to one another (about 2 inches apart), and the distances are gradually increased as they approach the muzzle; but close as they are at the seat of the shot

they could advantageously be closer still—say, half the distance—and they would have been so had we not been afraid to add more to the many holes we have bored in a gun destined to be so severely tested.

In working out the results for the first 6 inches of motion, the times, velocities, and pressures are interpolated for every $\frac{1}{50}$th of a foot; after that distance up to 3 feet, for every $\frac{1}{10}$th of a foot; and for the remainder of the bore, for every 6 inches.

Our experiments with the 2-inch gun do not call for much remark, save that in this calibre the differences between samples of the same class of powder of different manufacture were very strikingly shown, the maximum pressure of one sample of powder of professedly the same make being in some cases nearly double that of other samples.

But when we commenced our experiments with the 8-inch gun we were at once brought in contact with some very singular anomalies. Our first experiments with this gun were made with the Rodman gauge and the chronoscope only, and our attention was directed chiefly to two points—the different action of various kinds of powder, and the effect on the same kinds of powder of lighting the cartridge in a different position. On firing 20-lb. charges of the service powder—technically known as R. L. G.—with the vent in the position in which it is generally used in service, that is, at a distance of $\frac{4}{10}$ths the length of the battering charge from the bottom of the bore, not only did we find the Rodman gauges placed as I have described differ very materially in their results one from the other, but they all indicated a pressure very much higher than that shown by the chronoscope, the maximum chronoscope pressure being 17 tons per square inch, while the maximum pressure of the Rodman gauges varied from 28 tons to 33 tons on the square inch.

We then fired a series with the same charge and powder, using instead of the service vent a vent lighting the cartridge in the rear and here the results were still more anomalous. The chronoscope showed a maximum pressure differing but very slightly from the result when the service vent was used, while the Rodman gauge at the point C indicated a pressure of 50 tons.

These discrepancies threw some doubt on the accuracy of the indications of the Rodman gauge, and we were led to ascribe this inaccuracy to two causes—first, to the position* of the gauge on the

* It must be remembered that this defect, due to position, has no existence in many of the experiments with the Rodman gauge made on the Continent, because in the Continental experiments breach-loading guns have been generally used and the

outside of the gun; secondly, to what appeared to us to be a slight defect in the design of the gauge.

You will easily see our grounds for suspecting the effect which the position of the gauge might have if I recall to your recollection the experiment of Mr Robins, to which I alluded early this evening —namely, the enormous local pressure he found in a musket-barrel when he placed the bullet a considerable distance in front of the charge. In the Rodman gauge the indenting piston may be taken to represent Robin's bullet, and you will observe the distance the gas has to travel before it reaches the indenting tool.

The slight defect I have mentioned in the design of the Rodman gauge I may thus explain. Suppose the indenting tool, instead of pressing against the copper as shown, was removed from it by any given space, the gun then fired, and the gas allowed to act, it is obvious that the indication given by the copper could not be relied on, because, in addition to the pressure, the indenting tool would express on the copper the *vis viva* due to the velocity it had acquired when moving freely. In the Rodman knife the resistance to the motion of the indenting tool commences at zero and rapidly increases; but it is possible to conceive that the velocity* imparted to the tool when the resistance is but small may to some extent affect the amount of the indicated pressure.

The crusher gauge which I have described, and which admits of being applied either close to the interior of the bore or at the exterior of the gun, was thenceforth generally substituted for the Rodman gauge; and I may mention, as a proof of the correctness of our views, that in quick-burning powders this gauge, when applied at the outside of the 8-inch gun, gave pressures about double of those it indicated when applied to the inside.

The powders with which we have experimented may be divided into four classes—1. The old quick-burning, violent powders, such as R. L. G. and L. G.; 2. Pellet Powder; 3. Pebble Powder; and 4. Prismatic Powder. (See Fig. 14, p. 74.)

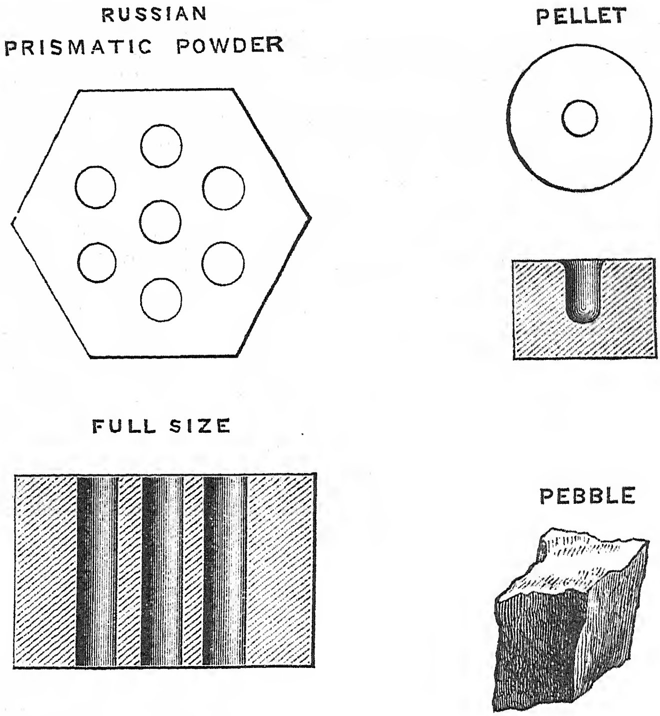
Here is a sample of the service R. L. G., and I will only remark

gauge has been applied to the wedge which closes the breach, and in this position would give satisfactory results; on the other hand, the pressure would only be obtained at one point, and such a determination, our experiments show, is not to be relied on.

* I was informed by General Gadolin, in Paris, that the results of the experiments made with the Rodman gauge in Russia were found to be uniform and satisfactory, only when prior to the experiments an indent was made in the copper a little less than that expected to be produced in the gun. This fact may be explained by the considerations referred to in the text.

that our old rule of proof for powder, that of the eprouvette mortar, seems, with our present lights, to be specially designed to produce in powder those qualities whose absence we most desire. Here are samples of pellet and pebble powders. You will notice that the former are regular cylinders formed in moulds, while the latter are tolerably regular lumps of powder cake, about the size of large pebbles; and, lastly, here is a sample of the prismatic powder which has attained so considerable a reputation on the Continent.

Fig. 14.

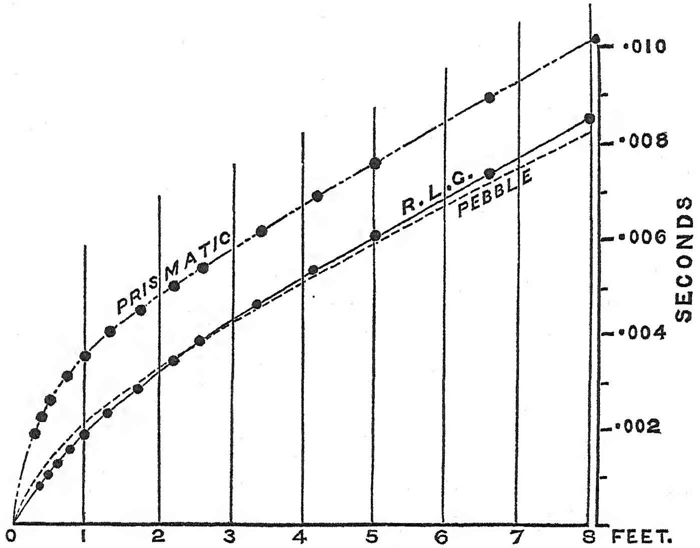


Any one of the three last classes is very much superior to the first. There is, in fact, no great difference, except as regards process of manufacture, between the pellet and pebble. Both give, when properly made, good results, although there seems to be a greater probability of attaining uniform results with the pellet than the pebble; but the prismatic differs considerably from these in being a less dense powder, and possessing the property of lighting with extreme slowness, as you will see by comparing its velocity or time curves with those of either pebble or R. L. G. I might characterise, perhaps, R. L. G. as a quick-lighting and extremely quick-burning

powder; pellet and pebble as quick-lighting, slow-burning powders; and prismatic as slow-lighting and quick-burning powder. It is probable that the prismatic powder owes it extreme slowness of lighting to the deposition of a heavy coating of saltpetre, due to the moisture present in the process of manufacture.

Although we find that almost inappreciable differences in the manufacture cause occasionally great differences of action when the powder is submitted to the test of firing, we are able to point to several causes which are of the greatest importance in modifying the behaviour of the powder in the gun. These points are—1. Specific gravity; 2. Length of time during which the component charcoal

Fig. 15.



has been burned; 3. Degree of moisture employed in manufacture; 4. Hardness; 5. Size of grain.

I have arranged on diagrams curves intended to illustrate the differences between three of the classes of powder I have been describing, and in each case I have selected an example which I believe to be as nearly as possible a type of the class. For the purpose of comparison, they are all taken from experiments with the 10-inch gun.

On this diagram, Fig. 15,* are delineated the time curves, that is,

* In this and the following figure the black dots denote the observed points. In each figure, however, to prevent confusion, the dots are omitted in the case of one curve.

the indications given by the chronoscope itself; the abscissæ represent the lengths of bore; the ordinates, the total time the shot takes to reach those lengths from the commencement of motion. This curve represents R. L. G., this pebble, and this prismatic. Note

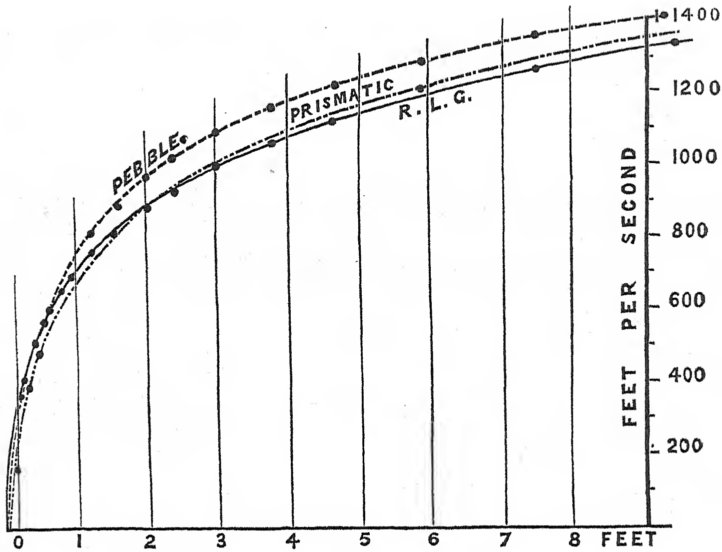


FIG. 16.

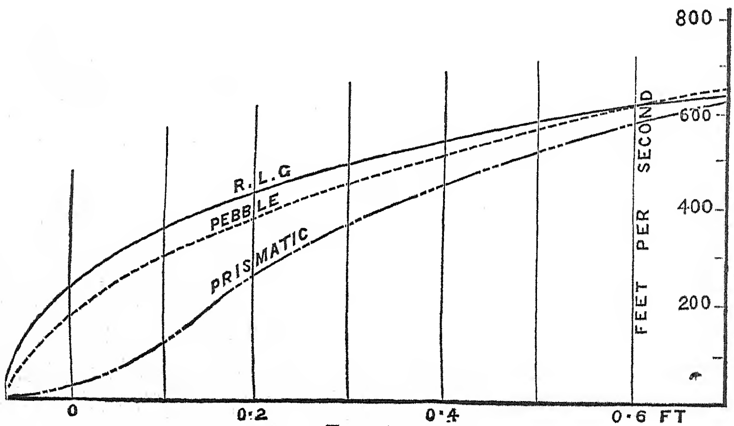


FIG. 17.

how much less is the time taken by the shot in the earlier parts of its motion in the case of R. L. G. and pebble than in that of prismatic.

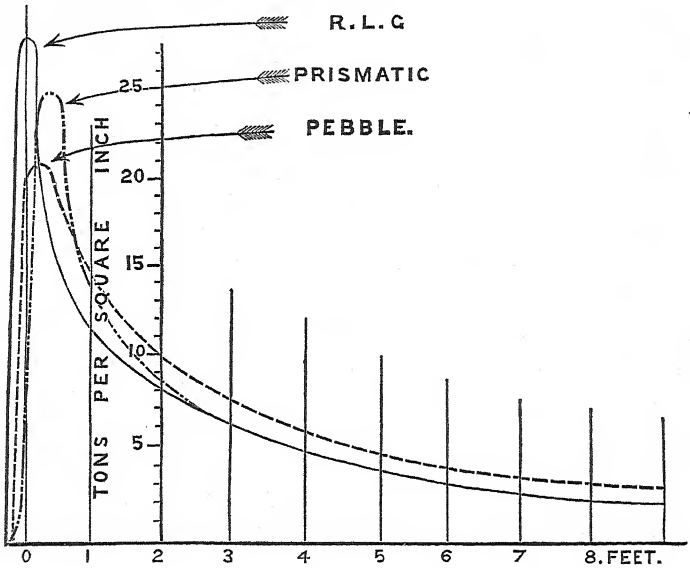
It may be interesting to mention that the total time taken by a projectile, when fired with a battering charge, to reach the muzzle of a 10-inch gun is about the $\frac{1}{100}$th part of a second.

The velocities at each point of the bore, deduced from these time curves, are here exhibited, Figs. 16 and 17.* Observe how, in the pebble and prismatic powders, the velocity commences by being considerably lower than the R. L. G. velocity; how they gradually reach it, pass it, and the projectile finally quits the gun, possessing a very considerably higher velocity.

The curves towards the muzzle pass very nearly through the observed velocities. Near the origin of motion the curves pass above the observed points, as they necessarily would do.

These curves, again, Fig. 18, represent the pressures correspond-

Fig. 18.



ing to those velocities, and their area is the measure of the work done by the respective powders on the shot.

You will note that with both the prismatic and pebble powders, although the maximum pressure is considerably less than with the R. L. G., this area is considerably more than the R. L. G. area. Hence follows the important fact—not only by the use of pebble powder, for example, is the gun much less strained than by the use of R. L. G., but we actually obtain from our gun, with the charges

* As, owing to the small scale of Fig. 16, giving the velocities throughout the bore, the differences in velocity near the commencement of motion are not readily perceptible, the same curves for the first 0·6 feet of motion have been laid down to a larger scale in Fig. 17.

we are enabled to use, nearly 20 per cent. more effect, the work done by the former powder being about 5700 foot tons, while by the latter it is only 4900 foot tons.

The pressures indicated by these curves are obtained from the chronoscope indications, and I now propose to examine what are the corresponding indications with the crusher gauge. They are as follow:—With the pebble, pellet, and prismatic powders, under ordinary circumstances, that is to say, with ordinary or battering charges of the service and with service vents, the pressure indicated by the crushers placed in the powder chamber in the positions marked A, B, C, do not differ materially from one another, and any of them, or the mean of the whole of them, agree tolerably closely with the maximum pressure indicated by the chronoscope. But when we come to R. L. G. or L. G. powders, a striking difference manifests itself; not only do the pressures in R. L. G. differ very materially from the indications given by the chronoscope, but they differ widely from one another. It is hardly necessary for me to point out to you that on the ordinary theory of the distribution of gas in the powder chamber in the first moments of motion, the density and consequent tension of gas should be least next the shot, and should gradually, but not very greatly, increase towards the bottom of the bore. This, however, was not at all so. Thus, for example, with one specimen of R. L. G., while the chronoscope pressure was found to be 28·3 tons, the pressure indicated by the crushers at C was 28·0 tons, at B was 31·3 tons, and at A was 47·9 tons. From other circumstances we were well aware that when similar charges and powder were fired with a rear centre vent, the destructive action on the gun was much reduced, but unfortunately with the destructive action was reduced also the useful effect. On our making the experiment, however, we found the chronoscope maximum pressure 19 tons instead of 28 tons, while the crusher pressure indicated at B was 26 tons instead of 31 tons, and at C 39 tons instead of 28 tons. What then was the cause of these striking differences? I may point out that there is no manner of doubt as to the reality of the facts indicated by the crushers; not only do they appear, round after round, with unfailing regularity, but we have tested the correctness of the results in every way our ingenuity could suggest. We are therefore met in the case of the destructive powders with difficulties which do not exist in the case of slow-burning powders, and as we are compelled to admit that some of these pressures are entirely local, or

confined to certain portions of the gun, we give the following explanation.

I need hardly again recall to your memory the early experiment of Robins, and the high local pressure he obtained by placing the musket-bullet at some distance from the charge. The explanation of this phenomenon doubtless is that the inflamed gas, vapours, or other products of explosion arising from the combustion of the powder attained a very high velocity before encountering the resistance of the bullet, and the reconversion of the *vis viva* into pressure accounts for the intense local pressure that Robins observed. The local pressure we have observed can be similarly explained. The *vis viva* of the products of combustion of the first portion of the charge ignited is in like manner converted into pressure at the seat of the shot, and as we know that the rapidity of combustion of powder is enormously accelerated by the tension under which it is exploded, it is possible that this pressure may be increased by a violent disengagement of gas from the unconsumed powder at the seat of the shot.

The crusher pressure indicated with the rear vent is, as we might expect from the increased run, considerably higher than when the service vent is used.

The time during which this abnormal pressure is kept up must be exceedingly minute, even when compared with the infinitesimal times we are considering, for we find the chronoscope pressure, which may be regarded in the case of these "poudres brutales" as representing the mean of pressures of a violent oscillatory character, hardly altered at all, even although the local pressures—as, for instance, when the rear vent is used—are increased 50 per cent.

Other indications also, which I shall shortly notice, lead to the same conclusion; but it is worthy of remark that, when violent local pressures are set up, waves of pressure, so to speak, appear to sweep from one end of the inflamed gases to the other, and to continue more or less during the whole time the shot is in the bore.

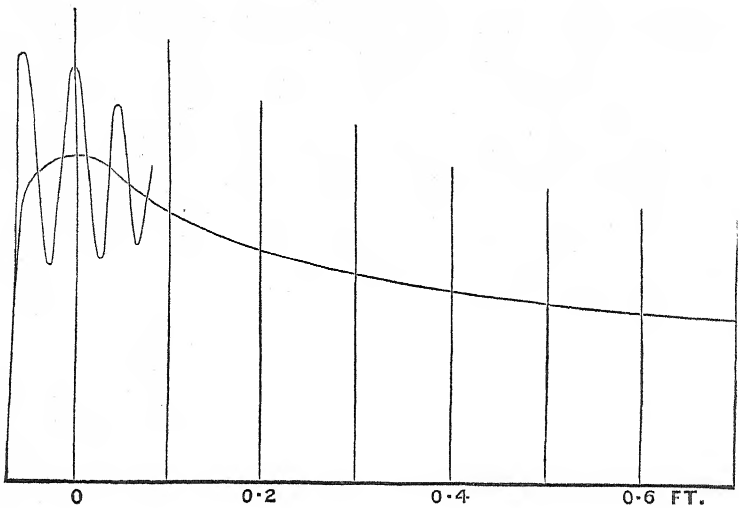
We are led to this conclusion from the following:—

With pebble and other powders, where no wave action is set up, the pressures indicated by the crushers throughout the bore agree satisfactorily with those indicated by the chronoscope, and the area of a curve drawn through the observations represents with tolerable accuracy the work done on the shot, but when

wave action is set up this no longer holds. The velocity of the shot may be the same, or even less, and of course the area of which I have spoken should correspond. On the contrary, however, it is always greater—frequently enormously so—representing 60 to 70 per cent. more work than is really done on the shot.

I have drawn on this pressure curve, Fig. 19, belonging to R. L. G., an imaginary line showing the way in which we may suppose these violent oscillations to exist; you will observe that oscillations of this character would not only explain the anomalies obtained with the crusher, but would explain also the double maxima invariably observed by General Neumann's Committee.

Fig. 19.



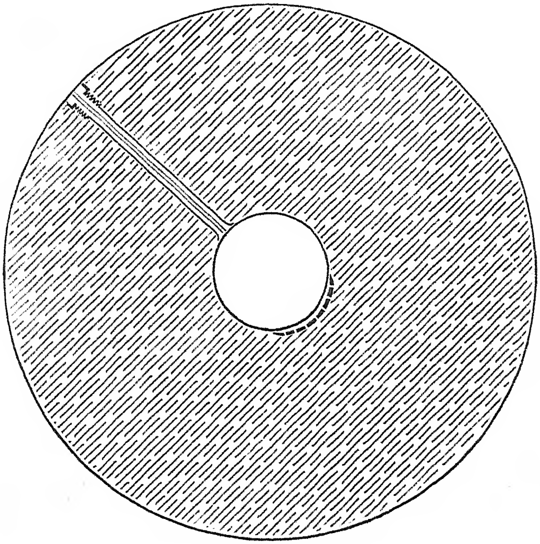
I will only add that the chronoscope and crusher in these investigations appear to me to be complementary one to the other. The chronoscope hardly recognises the existence of the local pressures; on the other hand, the crusher frequently gives no clue whatever to the mean pressure existing in the chamber.

The above remarks as to local pressures apply to quick-firing powders. With service vents and service charges this wave action scarcely seems to exist in the other powders I have discussed; but if the charge be greatly increased in length, more especially if the cartridge be lighted from the rear, it again appears. It must be remembered that, objectionable, for many reasons, as this action is, it is in no way so serious as if the local pressure extended simultaneously throughout the

chamber. In fact, certain considerations, with which I need not trouble you, led me to the conclusion that it was possible that under certain circumstances the maxima of the local pressure might be confined, not only to a certain portion in the longitudinal section of the bore, but even to a certain small arc in the transverse section through that portion.

I therefore caused the records of proof of certain 10-inch guns which have been proved at Elswick in a manner calculated to produce in a high degree local pressures, to be examined, and found that out of 26 guns 16 had, after proof, no expansion at

Fig. 20.



all, 2 were expanded in a very narrow rim all round at the seat of the shot, and the remainder, 8 in number, had small enlargements technically called dents, but the whole of these dents were confined to the seat of the shot, and to that portion of the section nearly opposite the vent which I have indicated in this diagram, Fig. 20.

Again, it is almost certain that the high local pressure indicated at the bottom of the bore in the 10-inch guns is confined to the particular point where the crusher is placed, and is due to the contraction of the bore towards the end.

To one difficulty I must allude.

In the quick-burning powders, at all events, it seems to be certain

that all, or at least all but a very trivial quantity, of the powder is converted into gas by the combustion of the powder before the projectile has been materially moved from its initial position. A glance at one of these pressure diagrams must convince you of this fact; but this being the case, how are we to account for the great loss of work which results when, under ordinary circumstances, a charge is ignited from the rear vent? This loss is very variable, but in one instance in our own experiments the work realised in the shot was reduced from 78 foot tons to 58 foot tons per lb. of powder.

The cause of this great loss of work, in an instance where it is difficult to believe that any quantity of powder can have escaped ignition, may, perhaps, be sought either on the hypothesis that under this peculiar mode of ignition the products of combustion differ materially from those arising under ordinary circumstances, or, as heat plays so important a part in the pressure of fired gunpowder, it may possibly be surmised that with the rear vent a much greater waste of heat has resulted than in the case of the service vent. I believe it is generally assumed that the loss of work arising from the heat communicated to the gun is altogether insignificant. This is, however, not so.

Careful experiments were made on this head some years ago in Italy with rifles, the rifles being fired under three conditions—viz., with the bullet as usual, the bullet very considerably removed from the charge, and with no bullet at all.

The results were that in all cases the heat communicated to the barrel represented considerably more than one-third of the total work developed, according to Bunsen and Schischkoff, by the combustion of the powder, being greatest when the ball was placed at some distance from the charge, least when the rifle was loaded in the ordinary manner.

The loss of heat would be very different in the case of the large charges with which we are dealing, but it is still much too large to be neglected, and it is certain that where the wave action, to which I have so often adverted, is set up, there is always a considerable loss of useful effect.

We are not, however, disposed to theorise too closely on the anomalies to which I have referred, as I believe I may say we have reasonable hopes of being able to solve some of our difficulties.

Collaterally with the researches of the Committee on the action of gunpowder in guns, I have made at Elswick a series of experiments on the tension of the gases in closed vessels.

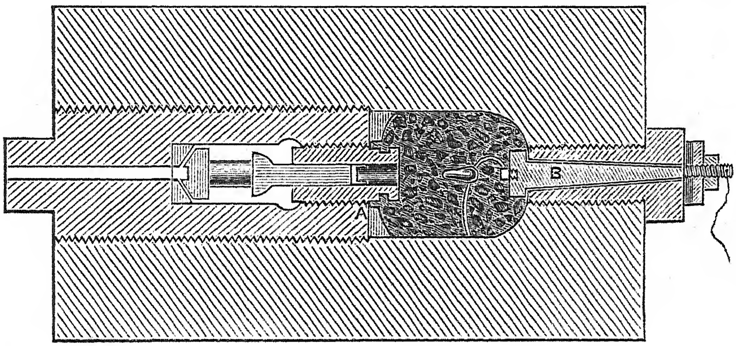
On the same diagram (Fig. 2, p. 56) in which I have placed Rumford's and Rodman's experiments I have plotted down our Elswick experiments, a portion of which were undertaken at the suggestion of General Lefroy.

Rumford only succeeded in determining the tension of the powder-gases when the powder occupied less than 70 per cent. of the space in which it was fired. His charges also were insignificant, and his results, possibly from faults arising from his mode of operation, are extravagantly high. Rodman's results, owing to the defect I have pointed out in his instrument, are also high, but he did not determine the tension where the powder occupied a larger proportion of the space than 50 per cent.

At Elswick, however, we have been so fortunate as not only to determine the tension of the gases at various densities, but we have exploded charges filling entirely the chambers of close vessels, and have altogether retained, and, by means of a special arrangement, discharged at pleasure the gaseous products of combustion.

The results of our experiments, all with Government R. L. G., are shown in the diagram, and it only remains for me to describe the apparatus with which we obtained our results. It is here shown (Fig. 21):—

FIG. 21.



The inflamed products are confined in the chamber by means of this gas check. The pressure is determined by means of a crusher arrangement fitted at A. The charge is exploded by means of one of Mr Abel's fuzes. The current passes through this insulated cone, B, which, the moment the charge is fired, destroys the insulating material and effectually closes the passage. The details of one or two of these experiments will be interesting to you. When we first made the arrangement for confining the powder absolutely, I thought

that the best method of stopping the escape of the gas was to make a steel vent, closing it with a gun-metal plug faced with tin. This arrangement was apparently successful. When I had just got up to the cylinder, and was stooping down to feel its heat, the charge suddenly made its escape with considerable violence. When the cylinder was opened for examination it was found that the escape of the gas was due to the heat of the explosion having melted the tin between the conical plug, and through the melted tin the gas readily escaped.

Another most remarkable occurrence was noted in the examination of this cylinder. On taking out the crusher apparatus, to my surprise I found that a portion of the solid steel projecting into the charge had been melted, and apparently run; also the head of a hardened steel screw had evidently fused. I hold in my hand these evidences of fusion, and call your attention to the exceedingly short time, 32 seconds, in which these effects were produced. By way of comparison, I put, for 37 seconds, into one of the hottest of Siemen's regenerative furnaces, at a temperature probably of about 3300° Fahr., a similar piece of steel. It was raised only to a heat of about 180° Fahr.

I must warn you, however, that the temperature of this fusion may have been seriously affected by chemical changes through which the fused metal may have passed; but an examination which I hope to have shortly made will settle this point.

With one other experiment I must trouble you. In the experiment I have just related I determined the tension of three-quarters of a pound of R. L. G. powder, completely filling the chamber in which it was fired, and having no escape whatever, to be about 32 tons on the square inch. For the purpose of my lecture this evening, I determined to make a similar experiment with F. G. and pellet. I have done so, and the results were completely successful. The gas was entirely confined. In the first case, when I got up to the cylinder it was making a singular crepitating noise, due probably to the sudden application of great internal heat. The temperature of the exterior of the cylinder rose rapidly to 111° Fahr., and then remained nearly stationary for some time. I then let the gases escape, which they did with a sharp, hissing noise, rising to a scream when any obstacle was placed on the orifice. With the escaping gases there was not the slightest appearance of smoke, vapour, or colour of any kind. The pressure indicated by the F. G. was 37 tons on the square inch, or about 5600 atmospheres.

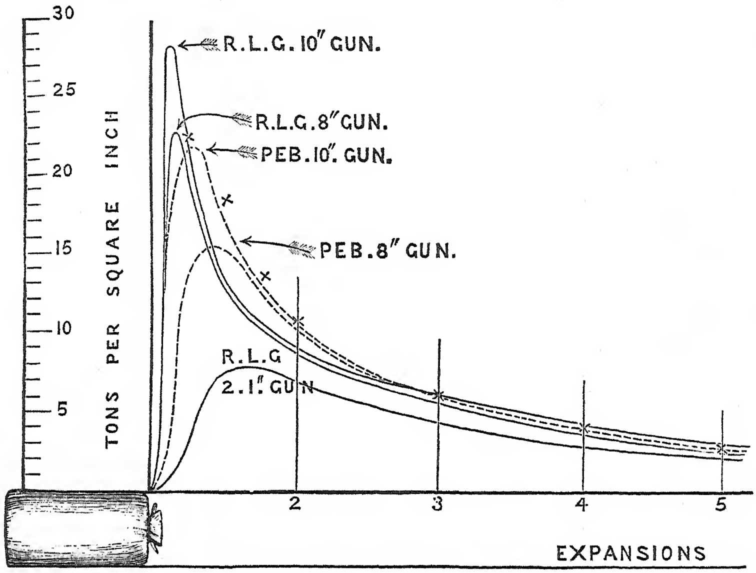
Here, in these sealed bottles, are the solid residues of combustion

from the F. G. and also from pebble. In each cylinder had been placed platinum wire and foil of different degrees of thickness. These have disappeared, and I am unable to say in what state they now are, until the residues have been examined.

I look upon the success of these experiments as being of great importance.

Not only, with the assistance of my friend and colleague (on the Committee), Mr Abel, so well known for his researches in explosive substances, shall we be able to determine the various products of combustion when the powder is fired at its maximum pressure, but

Fig. 22.



we shall be able to determine whether any, and if so what, change in the products is due to combustion under varying pressure; we shall also be able to determine the heat of combustion, and solve other important questions.

To a remarkable coincidence and singular confirmation of the Committee's results I must draw your attention.

Upon my obtaining this curve, giving the relation between the tension and density of the powder-gases in a close chamber, I was anxious to see how these results would conform with similar ones obtained from our observations of the tension in the bores of guns.

Accordingly I laid down these curves anew, Fig. 22, representing

pebble-powder fired in 10-inch and 8-inch guns, and R. L. G. fired in 10-inch, 8-inch, and 2-inch guns, the ordinates as before representing the tension of the powder, but the abscissæ representing the density of the gas. You will perceive, under this view, how closely the 10-inch and 8-inch pebble and R. L. G. approximate. But when I came to put on the same diagram, as indicated by the crosses, the tensions I had obtained from powder fired in a close vessel, they were nearly absolutely identical with the results obtained in the 10-inch gun from pebble-powder.

The coincidence, you will agree, is too remarkable to be accidental.

The practical conclusions to be deduced from the investigations forming the subject of this lecture may be arranged as follows:—

1st.—The maximum pressure of fired ordinary gunpowder, density being unity unrelieved by expansion, is not much above 40 tons to the square inch.

2nd.—In large guns, owing to the violent oscillations produced by the ignition of a large mass of powder, the pressure of the gas is liable to be locally exalted, even above its normal tension, in a perfectly closed vessel, and this intensification of pressure endangers the endurance of the gun, while detracting from the useful effect.

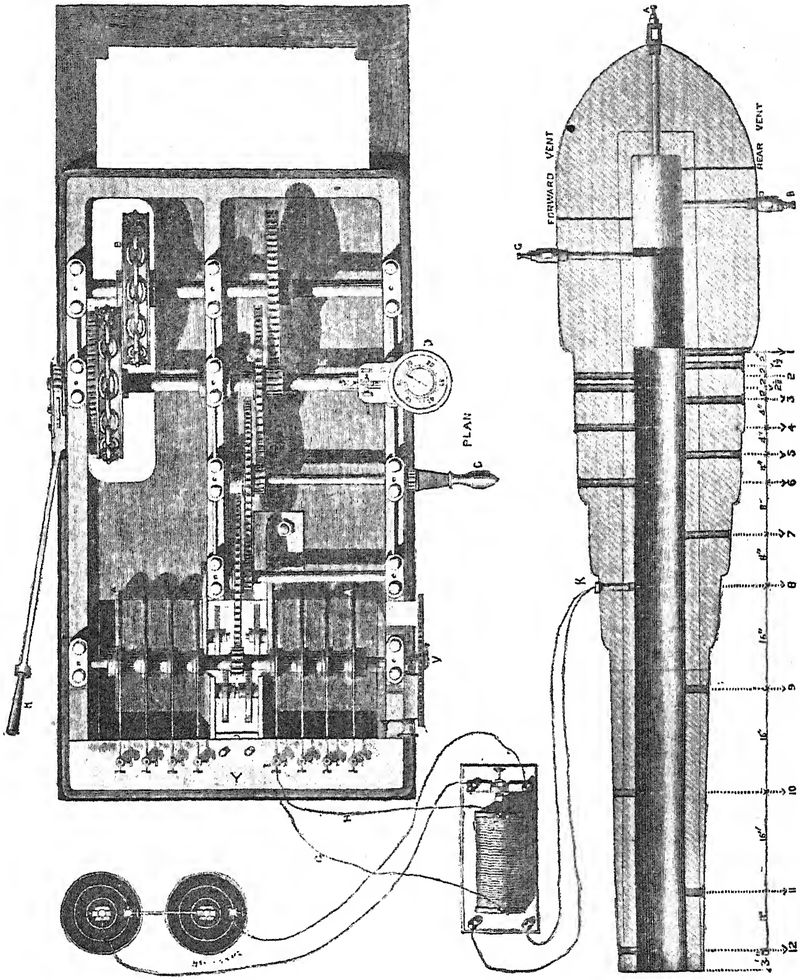
3rd.—Where large charges are used, quick-burning powder for the same energy greatly increases the strain upon the gun.

4th.—The position of the vent or firing point exercises an important influence upon the intensity of wave action, and in further enlarging the dimensions of heavy guns we must look to improved powder, and improved methods of firing the charge, so as to avoid as much as possible throwing the ignited gases into violent oscillation.

5th.—In all cases it is desirable to have the charges as short as possible, and the cartridge so lighted as to reduce the run of the gas to the shortest limit.

But I must conclude, and, while regretting the imperfect and incomplete information which I have been able this evening to give you, I trust you will remember that our investigations are still proceeding, and that, should the subject be of interest to you, and our work seem of sufficient importance, I or some other member of our Committee may yet be able to lay before you the results of our further researches.

PLATE VI.



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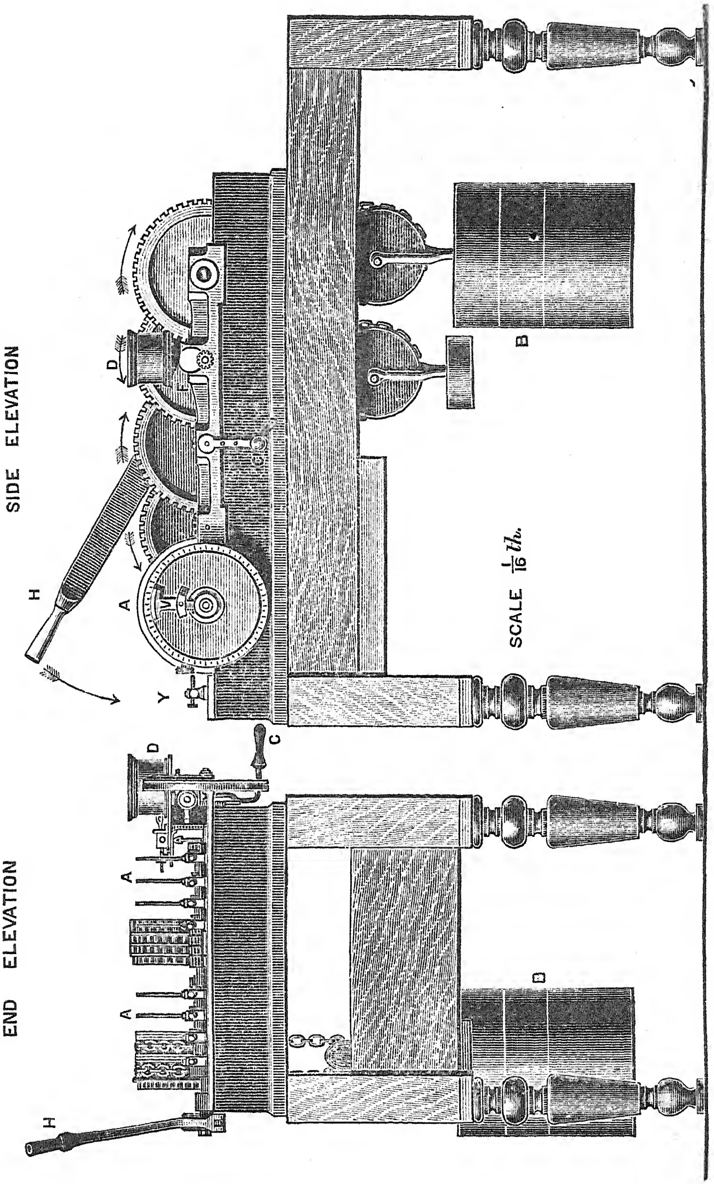

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V.

ON THE PRESSURE REQUIRED TO GIVE ROTATION TO RIFLED PROJECTILES.

(*Philosophical Magazine*, 1873.)

1. In a paper published in the *Philosophical Magazine* for 1863 (vol. xxvi.), and subsequently in the *Revue de Technologie Militaire,* I gave some investigations on the ratio between the forces tending to produce translation and rotation in the bores of rifled guns.

2. My object in these investigations was to show, 1st, that in the rifled guns with which experiments were then being made the force required to give rotation was generally only a small fraction of that required to give translation; 2ndly, that in all cases (and this was a point about which much discussion had taken place) the increment of gaseous pressure (that is, the increase of bursting force) due to rifling was quite insignificant.

3. In the paper referred to, although the formulæ were sufficiently general to embrace the various systems of rifling then under consideration in England, they did not include the case of an increasing twist, which has since been adopted for the 8-inch and all larger guns of the British service; neither was our knowledge of the pressure of fired gunpowder sufficient to enable me to place absolute values on either of the forces I was considering.

4. Since the date at which I wrote, an extensive series of experiments has been made in this country; and the results of these experiments enable me to give with very considerable accuracy both the pressure acting on the base of the projectile and the velocity at any point of the bore. I am therefore now able not only to assign absolute values where in my former paper I only gave ratios, but also to show the amount by which the studs of the projectiles of heavy guns have been relieved by the introduction of the accelerating twist known as the parabolic system of rifling.

5. Very little consideration will satisfy any one conversant with the subject, that in the ordinary uniform spiral or twist the pressure on the studs or other driving-surface is a maximum when the pressure on the base of the shot is a maximum, and becomes greatly reduced during the passage of the shot from its seat to the muzzle of the gun. In my former paper I showed, in fact, that in a uniform twist the pressure on the studs was a constant fraction of the pressure on the base of the shot, the value of the fraction of course depending on the angle of the rifling; and as it is evident that the tension of the powder-gases at the muzzle is very small when compared with the tension of the same gases at the seat of the shot, it follows that in such a system of rifling the studs may have scarcely any work to do at the muzzle, while they may be severely strained at the commencement of motion.

6. If, then, the defect of the ordinary or uniform system of rifling be that the studs are severely strained at the first instants of motion and are insignificantly strained at the instant of quitting the gun, it is obvious that it is possible to remove this inequality and at the same time allow the projectile to leave the bore with the same angular velocity by reducing the twist at the seat of the shot and gradually increasing it until it gains the desired angle at the muzzle. In fact, if we know the law according to which the pressure of the powder varies throughout the bore, it is theoretically possible to devise a system of rifling which shall give a uniform pressure on the studs throughout the bore.

7. These reasons doubtless led the late Ordnance Select Committee, to whom the application of the increasing twist to the service guns is due, to propose its introduction; and they selected as the simplest form of an increasing spiral the curve which, when developed on a plane surface, should have the increments of the angle of rifling uniform. This curve is, as is well known, a parabola; and as considerable advantages have been claimed for the parabolic system of rifling, I propose in this paper to examine and evaluate them.

I may add that I should not have given the results I now give, before the full experiments made by the Committee of Explosives, as well as some investigations undertaken by Mr Abel and myself are published, were it not that several groundless assertions concerning the Woolwich rifling have recently appeared, and have led to much discussion and very unnecessary uneasiness.

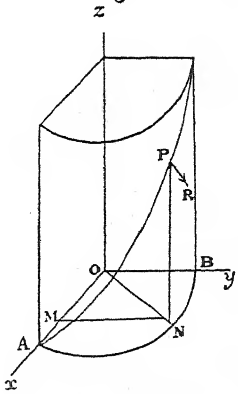
8. The argument commonly advanced against an accelerating twist is based upon the fact of the shot moving slowest at first, it

being supposed that while moving slowest the shot will require less force to make it rotate; but there is a fallacy in this argument, which lies in confounding velocity with rate of acceleration. The shot undoubtedly moves slowest at first, but it acquires velocity most rapidly at first, and it is the *gain* of velocity that determines the strain upon the stud.

9. The first question, then, which I propose is, to determine the pressure on the studs of a projectile fired from a gun rifled on a parabolic or uniformly increasing twist; and in this investigation I shall adopt the notation used in my former paper.

10. Take, then, as the plane of xy a plane at right angles to the axis of the gun. If the angle of rifling commence at zero, increasing to, say one turn in n calibres, let the plane of xy pass through the commencement of the rifling; but if the rifling do not commence at zero, it will be found more convenient to make the plane of xy pass through the point where the twist would be zero were the grooves sufficiently prolonged. Let the axis of x pass through one of the grooves; and, for the sake of simplicity, we shall suppose the rifling to be given by one groove only. Let the axis of z be coincident with that of the gun; let AP (see Fig. 1) be the groove or curve described by the point P, and let P (x, y, z) be the point at which the resultant of all the pressures tending to produce rotation may be assumed to act at a given instant. Let the angle AON $= \phi$.

Fig. 1.



11. Now the projectile in its passage through the bore is acted on by the following forces:—

1st. The gaseous pressure G, the resultant of which acts along the axis of z.

2nd. The pressure tending to produce rotation. Calling this pressure R, and observing that it will be exerted normally to the surface of the groove, we have for the resolved parts of this pressure along the co-ordinate axes, R cos λ, R cos μ, and R cos ν; λ, μ, and ν being the angles which the normal makes with the co-ordinate axes.

3rd. The friction between the stud or rib of the projectile and the driving-surface of the groove. This force tends to retard the motion of the projectile; its direction will be along the tangent to the curve

which the point P describes. If μ_1 be the coefficient of friction, and if α, β, γ be the angles which the tangent makes with the co-ordinate axes, the resolved portions of this force are $\mu_1 \mathrm{R} \, . \cos \alpha$, $\mu_1 \mathrm{R} \, . \cos \beta$, $\mu_1 \mathrm{R} \, . \cos \gamma$.

12. Summing up these forces, the forces which act

$$\left.\begin{array}{lll} \text{parallel to } x \text{ are} & \mathrm{X} = & \mathrm{R}.\{\cos\lambda - \mu_1 \cos\alpha\} \\ \quad ,, \quad\; y \quad ,, & \mathrm{Y} = & \mathrm{R}.\{\cos\mu - \mu_1 \cos\beta\} \\ \quad ,, \quad\; z \quad ,, & \mathrm{Z} = & \mathrm{G} + \mathrm{R}.\{\cos\nu - \mu_1 \cos\gamma\} \end{array}\right\} \quad . \quad . \quad (1)$$

and the equations of motion are

$$\mathrm{M}.\frac{d^2z}{dt^2} = \mathrm{G} + \mathrm{R}\{\cos\nu - \mu_1 \cos\gamma\} \quad . \quad . \quad . \quad (2)$$

$$\mathrm{M}.\frac{d^2\phi}{dt^2} = \frac{\mathrm{Y}x - \mathrm{X}y}{\rho^2} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

ρ being the radius of gyration. Equations (1), (2), and (3) are identical with those I formerly gave.

13. Now, in the case of a uniformly increasing twist, the equations to the curve which when developed on a plane surface is a parabola may be put under the form

$$x = r\cos\phi; \quad y = r\sin\phi; \quad z^2 = kr\phi \quad . \quad . \quad . \quad (4)$$

Hence

$$dx = -r\sin\phi \, . \, d\phi; \quad dy = r\cos\phi \, . \, d\phi$$

$$dz = \frac{kr}{2z} \, . \, d\phi; \quad ds = \frac{r}{2z}\sqrt{4z^2 + k^2} \, . \, d\phi$$

and we have, to determine the angles which the tangent to the curve described by P makes with the co-ordinate axes, the equations

$$\left.\begin{array}{l} \cos\alpha = \dfrac{dx}{ds} = \dfrac{-2z \, . \sin\phi}{\sqrt{4z^2 + k^2}} \\ \cos\beta = \dfrac{dy}{ds} = \dfrac{2z \, . \cos\phi}{\sqrt{4z^2 + k^2}} \\ \cos\gamma = \dfrac{dz}{ds} = \dfrac{k}{\sqrt{4z^2 + k^2}} \end{array}\right\} \quad . \quad . \quad . \quad . \quad (5)$$

14. In the Woolwich guns the driving-surface of the groove may be taken, without sensible error, as the simpler form of surface where the normal to the driving-surface is perpendicular to the radius, the surface itself being generated by that radius of the bore which, passing perpendicularly through the axis of z, meets the curve described by the point P; but in the first instance I shall examine the more general case, where the normal makes any assigned angle with the radius.

Assume then that on the plane of xy the normal makes an angle δ with the radius of the gun. The driving-surface of the groove is then swept out by a straight line which, always remaining parallel to the plane of xy, intersects the curve described by P, and touches the right cylinder whose axis is coincident with that of z, and whose radius $= r \,.\, \cos \delta$.

Now, the equations to the director being given by (4), and that to the cylinder, which the generator always touches, being

$$x^2 + y^2 = (r \cos \delta)^2 \qquad \ldots \qquad (6)$$

it is easily shown that the co-ordinates x_1, y_1 of the point of contact of the tangent to the cylinder drawn from P parallel to the plane xy, are

$$\left.\begin{aligned} x_1 &= r \,.\, \cos \delta \,.\, \cos (\phi - \delta) \\ y_1 &= r \,.\, \cos \delta \,.\, \sin (\phi - \delta) \end{aligned}\right\} \qquad \ldots \qquad (7)$$

and that the equation to the driving-surface is

$$x \,.\, \cos \left\{\frac{z^2}{kr} - \delta\right\} + y \,.\, \sin \left\{\frac{z^2}{kr} - \delta\right\} = r \,.\, \cos \delta \qquad . \quad (8)$$

15. The angles which the normal to this surface make with the co-ordinate axes are given by

$$\cos \lambda = \frac{\left(\frac{d\mathrm{F}}{dx}\right)}{\sqrt{\left(\frac{d\mathrm{F}}{dx}\right)^2 + \left(\frac{d\mathrm{F}}{dy}\right)^2 + \left(\frac{d\mathrm{F}}{dz}\right)^2}}$$

with similar expressions for $\cos \mu$ and $\cos \nu$. But

$$\left(\frac{d\mathrm{F}}{dx}\right) = \cos\left(\frac{z^2}{kr} - \delta\right); \ \left(\frac{d\mathrm{F}}{dy}\right) = \sin\left(\frac{z^2}{kr} - \delta\right); \ \left(\frac{d\mathrm{F}}{dz}\right) = \frac{2z}{k} \,.\, \sin \delta$$

$$\sqrt{\left(\frac{d\mathrm{F}}{dx}\right)^2 + \left(\frac{d\mathrm{F}}{dy}\right)^2 + \left(\frac{d\mathrm{F}}{dz}\right)^2} = \frac{1}{k}\sqrt{4z^2(\sin \delta)^2 + k^2}$$

Therefore the angles which the normal to the driving-surface makes with the axes are given by

$$\left.\begin{aligned} \cos \lambda &= -\frac{k \,.\, \cos\left(\frac{z^2}{kr} - \delta\right)}{\sqrt{4z^2(\sin \delta)^2 + k^2}} \\ \cos \mu &= -\frac{k \,.\, \sin\left(\frac{z^2}{kr} - \delta\right)}{\sqrt{4z^2(\sin \delta)^2 + k^2}} \\ \cos \nu &= -\frac{2z \,.\, \sin \delta}{\sqrt{4z^2(\sin \delta)^2 + k^2}} \end{aligned}\right\} \qquad \ldots \qquad (9)$$

16. Substituting in (2) and (3) the values given for $\alpha, \beta, \gamma, \lambda, \mu, \nu$ in (5) and (9), the equations of motion become

$$\mathrm{M}\cdot\frac{d^2z}{dt^2} = \mathrm{G} - \mathrm{R}\left\{\frac{2z\sin\delta}{\sqrt{4z^2(\sin\delta)^2+k^2}} + \frac{\mu_1 k}{\sqrt{4z^2+k^2}}\right\} \quad . \quad (10)$$

$$\mathrm{M}\cdot\frac{d^2\phi}{dt^2} = \frac{\mathrm{R}\cdot r}{\rho^2}\left\{\frac{k\cdot\sin\delta}{\sqrt{4z^2(\sin\delta)^2+k^2}} - \frac{2\mu_1 z}{\sqrt{4z^2+k^2}}\right\} \quad . \quad (11)$$

and from (11),

$$\mathrm{R} = \frac{\mathrm{M}\cdot\rho^2}{r\left\{\dfrac{k\cdot\sin\delta}{\sqrt{4z^2(\sin\delta)^2+k^2}} - \dfrac{2\mu_1 z}{\sqrt{4z^2+k^2}}\right\}}\cdot\frac{d^2\phi}{dt^2} \quad . \quad . \quad (12)$$

17. To determine $\dfrac{d^2\phi}{dt^2}$

From (4) $\qquad kr\phi = z^2$

$$\therefore \quad kr\cdot\frac{d\phi}{dt} = 2z\cdot\frac{dz}{dt}$$

$$kr\cdot\frac{d^2\phi}{dt^2} = 2\cdot\left\{z\cdot\frac{d^2z}{dt^2} + \left(\frac{dz}{dt}\right)^2\right\}$$

$$\therefore \quad \frac{d^2\phi}{dt^2} = \frac{2}{kr}\cdot\left\{z\cdot\frac{d^2z}{dt^2} + v^2\right\} \quad . \quad . \quad (13)$$

and substituting this value of $\dfrac{d^2\phi}{dt^2}$ in (12)

$$\mathrm{R} = \frac{2\mathrm{M}\rho^2}{kr^2\left\{\dfrac{k\cdot\sin\delta}{\sqrt{4z^2(\sin\delta)^2+k^2}} - \dfrac{2\mu_1 z}{\sqrt{4z^2+k^2}}\right\}}\cdot\left\{z\cdot\frac{d^2z}{dt^2} + v^2\right\}$$

or, for brevity,

$$= \mathrm{A}\left\{z\cdot\frac{d^2z}{dt^2} + v^2\right\}$$

or, substituting the value of $\dfrac{d^2z}{dt^2}$ derived from (10)

$$= \mathrm{A}\left\{\frac{\mathrm{G}\cdot z}{\mathrm{M}} - \frac{\mathrm{R}z}{\mathrm{M}}\left(\frac{2z\cdot\sin\delta}{\sqrt{4z^2(\sin\delta)^2+k^2}} + \frac{\mu_1 k}{\sqrt{4z^2+k^2}}\right) + v^2\right\}$$

and from this expression may be deduced

$$\mathrm{R} = \frac{2\rho^2\{\mathrm{G}z + \mathrm{M}v^2\}}{\dfrac{(k^2r^2+4\rho^2z^2)\sin\delta}{\sqrt{4z^2(\sin\delta)^2+k^2}} + \dfrac{2\mu_1 kz(\rho^2-r^2)}{\sqrt{4z^2+k^2}}} \quad . \quad . \quad (14)$$

18. Equation (14) gives the pressure acting between the studs or rib of the projectile and the driving-surface of the groove at any

point of the bore, and for any inclination of the driving-surface; but, as before stated, in the Woolwich guns the normal to the driving-surface (that is, the line of action of R) may, without material error, be considered as perpendicular to the radius.

If in (14) δ be put $=90°$, the equation is simplified; and the resulting expression gives the total pressure on the studs for the Woolwich guns.

Putting then $\delta=90°$, (14) becomes

$$R=\frac{2\rho^2\sqrt{4z^2+k^2}(Gz+Mv^2)}{kr^2(k-2\mu_1 z)+2\rho^2 z(2z+\mu_1 k)} \quad . \quad . \quad . \quad (15)$$

19. Compare now (14) and (15), the equations giving the pressure on the studs for parabolic rifling, with the equations subsisting where a uniform twist is used.

For a uniform twist we have, as I formerly showed,

$$R=\frac{2\pi\rho^2}{\dfrac{\mu_1(2\pi\rho^2 k-rh)}{\sqrt{1+k^2}}+\dfrac{(2\pi\rho^2+rhk)\sin\delta}{\sqrt{k^2+(\sin\delta)^2}}}\,.\,G\,. \quad . \quad (16)$$

where h is the pitch of the rifling, k the tangent of the angle which the groove makes with the plane of xy, the other constants bearing the meaning I have already assigned to them in this investigation.

20. In the Woolwich guns, where $\delta=90°$, (16) becomes

$$R=\frac{2\pi\rho^2\sqrt{1+k^2}}{hr(k-\mu_1)+2\pi\rho^2(\mu_1 k+1)}\,.\,G \quad . \quad . \quad . \quad (17)$$

21. I proceed to apply these formulæ, and propose to examine what are the pressures actually required to give rotation to a 400-lb. projectile, fired from a 10-inch gun with battering charges, under the following conditions:—1st. If the gun be rifled with an increasing twist as at present. 2nd. If it be rifled with a uniform pitch, the projectile in both cases being supposed to have the same angular velocity on quitting the gun. As the calculations for the uniform pitch are the simpler, I shall take this case first.

22. I have before remarked that with a uniform twist the pressure on the studs of the projectile is a constant fraction of that on the base of the shot, and represents, so to speak, on a reduced scale, the pressure existing at any point in the bore of the gun. Calling the fraction in equation (17) C, we have

$$R=C\,.\,G \quad . \quad . \quad . \quad . \quad . \quad (18)$$

where

$$C = \frac{2\pi\rho^2\sqrt{1+k^2}}{hr(k-\mu_1)+2\pi\rho^2(\mu_1 k+1)} = \cdot 04426 \quad . \quad . \quad (19)$$

the values of the constants in (19) being in the case of the 10-inch gun as follow:—

$$\rho = \cdot 312 \text{ ft.}, \quad k = 12\cdot 732, \quad h = 33\cdot 333 \text{ ft.}, \quad r = \cdot 417 \text{ ft.}, \quad \mu_1 = \cdot 167$$

Hence

$$R = \cdot 04426 \,.\, G \quad . \quad . \quad . \quad . \quad . \quad (20)$$

23. But the values of G are known with very considerable exactness from the investigations of the Explosive Committee under the presidency of Colonel Younghusband. The following Table gives the value of G (that is, the total pressure in tons acting on the base of the projectile) for a charge of 70 lbs. of pebble-powder at various points of the bore, and the corresponding values of R. It will be remarked how high the pressure on the studs is when that on the base of the shot is a maximum, and how rapidly the strain decreases as the shot approaches the muzzle.

Table showing the pressure on the studs in a 10-*inch British-service gun rifled with a uniform twist, calculated from* (17).

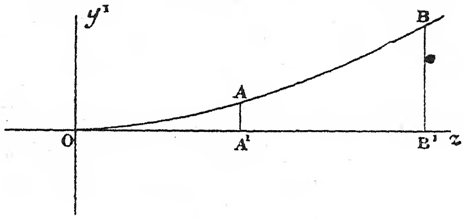
Travel of shot, in feet.	Total pressure G on base of shot, in tons.	Value of C.	Value of R, or total pressure on studs, in tons.
0·000	0	·04426	0
0·333	1547	,,	68·5
0·945	1077	,,	47·7
1·834	781	,,	34·6
2·723	621	,,	27·5
3·612	510	,,	22·6
4·500	424	,,	18·7
5·389	356	,,	15·8
6·278	305	,,	13·5
7·167	268	,,	11·8
8·055	240	,,	10·6
8·944	220	,,	9·7
9·833	205	,,	9·1

24 The results in the Table show the pressures required to give rotation, if the 10-inch gun be rifled on a uniform twist. I turn now to the rifling as it actually exists, and which is defined to be a parabolic twist, commencing with one turn in 100 calibres and terminating at the distance of 9·833 feet with a twist of one

turn in 40 calibres; and first to determine the equation to the parabola.

Let the origin be at the point where the twist vanishes when the curve AB is sufficiently prolonged—that is, at the vertex of the parabola. Let Oz and Oy' be the axes of co-ordinates; let $OA'=z_1$,

Fig. 2.



$OB'=z_2$; let $\tan\theta_1$ be the tangent of the angle which the curve makes with Oz at A, and $\tan\theta_2$ be the corresponding tangent at B.

Then, from the definition of the parabolic twist,

$$\frac{d^2y'}{dz^2} = \text{constant} = c, \text{ suppose}$$

$$\therefore \quad \frac{dy'}{dz} = cz \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

and

$$y' = \frac{c}{2}z^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

But, from (21),

$$\tan\theta_2 = cz_2, \text{ and } \tan\theta_1 = cz_1$$

$$\therefore \quad c = \frac{\tan\theta_2 - \tan\theta_1}{z_2 - z_1} = \cdot 0047925$$

Comparing (22) with the form of this equation given in (4),

$$z^2 = kr\phi, \text{ we have } y' = r\phi \text{ and } k = \frac{2}{c} = 417\cdot 3$$

Hence the equation to the development of the parabolic rifling is

$$z^2 = 417\cdot 3r\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

and z_1 the distance of the origin from the commencement of the rifling

$$= \frac{\tan\theta_1}{c} = 6\cdot 555 \text{ feet.}$$

25. As in the last case, I place in the form of a Table the results

given by (15) for different values of z. The values of the constants are,

$$r = \cdot 417 \text{ feet}, \ k = 417\cdot 3, \ \rho = \cdot 312 \text{ feet}, \ \mu_1 = \cdot 167, \ \text{M} = \cdot 00555$$

Table showing the pressure on the studs in a 10-*inch British-service gun rifled with a parabolic twist, commencing at one turn in* 100 *calibres and terminating at one turn in* 40 *calibres, calculated from* (15).

Value of z, the distance from the origin, in feet.	Corresponding travel of the shot in the bore, in feet.	Corresponding velocity of shot, in feet.	Total pressure on base of shot, in tons.	Value of R, or total pressure on studs, in tons.
6·555	0·000	0	0	0
6·888	0·333	411	1547	31·2
7·500	0·945	675	1077	28·7
8.389	1·834	873	781	29·0
9·278	2·723	992	621	30·2
10·167	3·612	1078	510	31·4
11·055	4·500	1146	424	32·3
11·944	5·389	1200	356	33·0
12·833	6·278	1245	305	33·8
13·722	7·167	1282	268	34·5
14·610	8·055	1311	240	35·2
15·499	8·944	1333	220	35·8
16·388	9·833	1349	205	36·3

26. From an examination of the values of R given in this Table, it will be seen that the total pressure on the driving-surface reaches about 31 tons shortly after the commencement of motion, and the projectile quits the bore with a pressure of about 36 tons. With the view of making the variations which the pressures undergo more readily comparable, I have laid down in the coloured Plate facing page 98 the curves derived from Equations (15) and (17) for the battering charge of pebble-powder.

From these diagrams the pressures on the driving-surface at any point of the bore, both for the uniform and parabolic twists, can be seen by simple inspection. The axis of abscissæ gives the travel of the shot, and the ordinates give the corresponding *total pressure* on the studs.

The curves show that with the uniform spiral the pressure on the studs reaches nearly 70 tons after a travel of ·3 feet, rapidly falling to about 9 tons at the muzzle, while with the parabolic rifling the pressure at ·3 feet of travel, corresponding to the point of maximum pressure, is only 31 tons. The pressure then falls slightly, and amounts to 28 tons at about 1 foot travel; thence it gradually increases to a maximum of 36 tons at the muzzle.

By way of comparison, I have added in the Plate a curve showing

the pressures required to give rotation to a 400-lb. projectile fired from the 10-inch gun with uniform twist when R. L. G. instead of pebble-powder is used.

The curve in this case is of the same nature as that derived from the pebble-powder; but the variation is greater, the maximum pressure being much higher, and the muzzle-pressure, owing to the smaller charge, somewhat less.

27. To one more point it is worth while to call attention.

If the gun were a smooth-bore gun, the equation of motion would be

$$M \cdot \frac{d^2z}{dt^2} = G' \quad . \quad . \quad . \quad . \quad (24)$$

and comparing this equation with (10), we have, on the supposition* that the velocity increments in both cases are equal,

$$G = G' + R \cdot \left\{ \frac{2z \cdot \sin \delta}{\sqrt{4z^2(\sin \delta)^2 + k^2}} + \frac{\mu_1 k}{\sqrt{4z^2 + k^2}} \right\} \quad . \quad . \quad (25)$$

or, in the case of the Woolwich gun, where $\delta = 90^\circ$,

$$G = G' + R \cdot \left\{ \frac{2z + \mu_1 k}{\sqrt{4z^2 + k^2}} \right\} \quad . \quad . \quad . \quad (26)$$

and the interpretation of these equations is that the gaseous pressure in the rifled guns (rifled with the parabolic twist) is greater than that in the smooth-bored gun by the second term of the right-hand member of the equation.

28. The corresponding equations for a uniform twist are

$$G = G' + R \left\{ \frac{\sin \delta}{\sqrt{k^2 + (\sin \delta)^2}} + \frac{\mu_1 k}{\sqrt{1 + k^2}} \right\} \quad . \quad . \quad (27)$$

or, if $\delta = 90^\circ$,

$$G = G' + R \left\{ \frac{\mu_1 k + 1}{\sqrt{1 + k^2}} \right\} \quad . \quad . \quad . \quad . \quad (28)$$

29. I shall now put these results in actual figures, and shall again take for illustration the 10-inch gun, supposed (as before) to be rifled, 1st, on the uniform, 2nd, on the parabolic or service twist.

With the uniform twist, G (see Table) = 1547 tons; and using Equation (28) and the values of the constants given in 22,

$$\begin{aligned} G' &= G - {\cdot}245R \\ &= {\cdot}989G \quad . \quad . \quad . \quad . \quad . \quad . \quad (29) \end{aligned}$$

---

* Were the velocity increments not supposed equal, the reduction of pressure due to the suppression of rifling would be less than that given in the text.

Hence the decrement of pressure due to the suppression of rifling is only about 1 per cent.; that is, the total pressure on the base of the shot is reduced from 1547 tons to 1530 tons, or the bursting pressure is reduced from 19·7 tons per square inch to 19·5 tons per square inch.

At the muzzle of the gun in the same manner we find that the total pressure is reduced from 205 tons to 202·8 tons, and the pressure per inch in a corresponding proportion.

30. Similarly, from Equation (26) and the values of the constants given in 25, the values of G' at the point of maximum pressure and at the muzzle of the gun are obtained; and I find that with the parabolic twist the pressure on the base of the shot would be reduced from 1547 tons to 1541 tons, or the bursting pressure would be reduced from 19·7 tons to 19·62 tons per square inch.

At the muzzle the corresponding reductions are from 205 tons total pressure, to 196 tons, or from 2·61 tons to 2·49 tons per square inch.

31. For the sake of clearness, I recapitulate the results at which I have arrived. They are as follows:—

1st. That the pressures actually exerted at all points of the bore to give rotation to the 10-inch British-service projectile, compared with the pressures which would be exerted were the gun rifled on a uniform twist, are very approximately exhibited in the diagrams on Plate VIII.

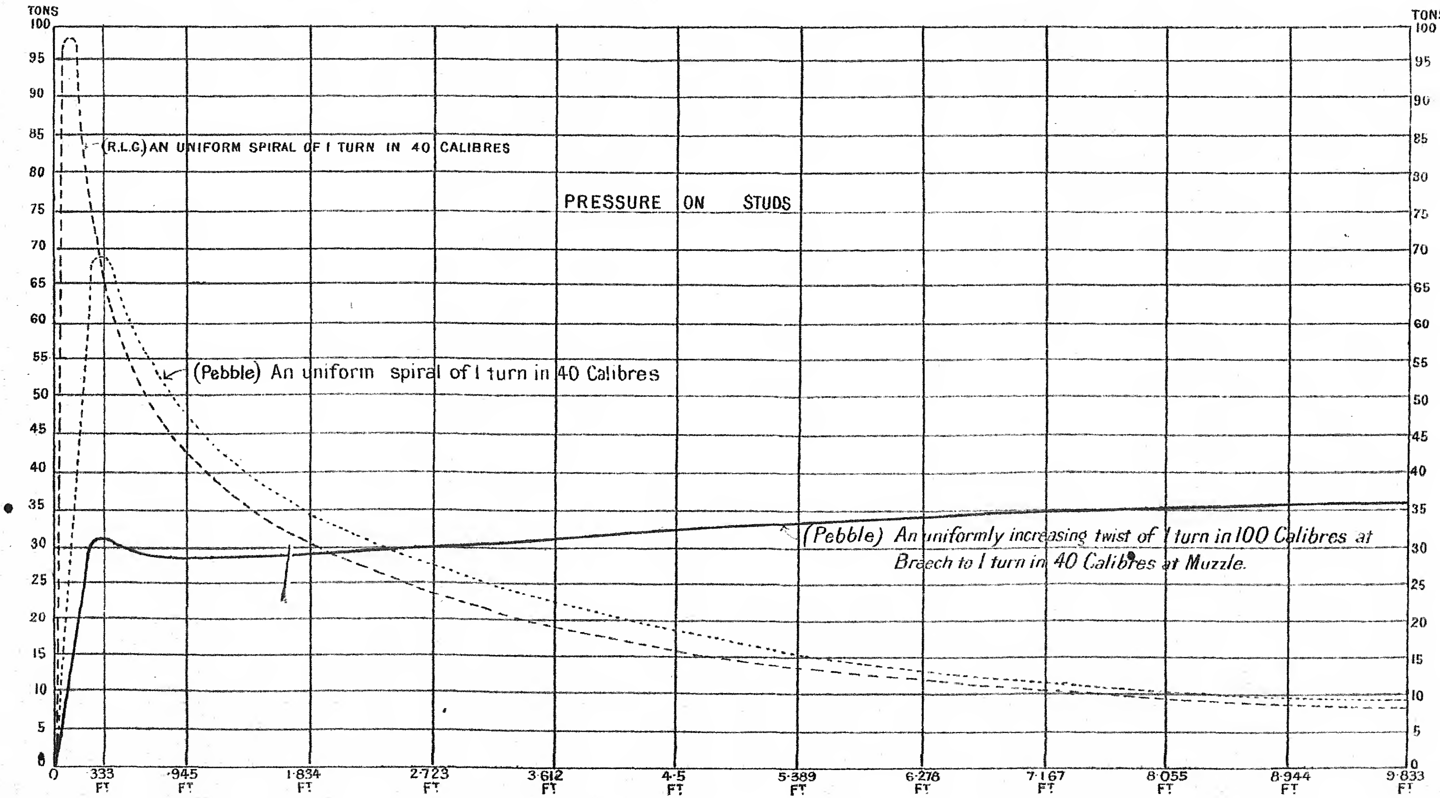
2nd. That in the 10-inch gun (and other guns similarly rifled) the pressure on the studs due to rifling is but a small fraction (about $2\frac{1}{4}$ per cent.) of the pressure required to give translation to the shot.

3rd. That the substitution of the parabolic for the uniform rifling has reduced by about one-half the maximum pressure on the studs.

4th. That the increment of the gaseous pressure, or the pressure tending to burst the gun, due to rifling is exceedingly small,* both in the case of the uniform and parabolic rifling. This result is entirely confirmed by the experiments of the Explosive Committee, who have found no sensible difference of pressure in the 10-inch gun fired in the rifled and unrifled states.

5th. That, small as the increment in gaseous pressure due to rifling is, it is still less in the parabolic than in the uniform system of rifling.

* Although the increase of strain due to rifling is inconsiderable, yet the decrease of the strength of the structure of a gun inseparable from rifling may be, and in many systems is, considerable; but the discussion of this question is outside of the scope of my paper.


PRESSURE ON STUDS
(R.L.G.) AN UNIFORM SPIRAL OF 1 TURN IN 40 CALIBRES
(Pebble) An uniform spiral of 1 turn in 40 Calibres
(Pebble) An uniformly increasing twist of 1 turn in 100 Calibres at Breech to 1 turn in 40 Calibres at Muzzle.
TONS
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
·333 FT
·945 FT
1·834 FT
2·723 FT
3·612 FT
4·5 FT
5·389 FT
6·278 FT
7·167 FT
8·055 FT
8·944 FT
9·833 FT

VI.

RESEARCHES ON EXPLOSIVES.—PART I.

(FIRED GUNPOWDER.)

(Contributed, in collaboration with Sir FREDERICK ABEL, to the *Transactions of the Royal Society*, 1875 *and* 1879.)

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(*a*) INTRODUCTORY HISTORY

THE investigations which form the subject of this memoir have occupied our attention for a considerable time, having been commenced in 1868. They have been made collaterally with a series of experiments carried on by a Committee appointed by the Secretary of State for War, with the view, among other objects, of determining the most suitable description of powder for use in heavy ordnance, which is still continually increasing in size; indeed our main object has been to endeavour to throw additional light upon the intricate and difficult subject under investigation by that Committee.

There are perhaps few questions upon which, till within quite a recent date, such discordant opinions have been entertained as upon the phenomena and results which attend the combustion of gunpowder. As regards the question alone of the pressure developed, the estimates are most discordant, varying from the 1000 atmospheres of Robins to the 100,000 atmospheres of Rumford; or even, discarding these extreme opinions in favour of views which have been accepted in modern text-books as more reliable, the difference between an estimate of 2200 * and of 29,000 † atmospheres is sufficiently startling as regards a physical fact of so much importance. The views regarding the decomposition of gunpowder are nearly as various; and we therefore think that a description and discussion of our own researches may be usefully preceded by a short account of the

* Bloxam, C. L., *Chemistry, Inorganic and Organic*, 1867, p. 427. Owen, Lieut.-Col., R.A., *Principles and Practice of Modern Artillery*, 1871, p. 155.

† Piobert, G., *Traité d'Artillerie Théorique et Expérimentale*, 1859, pp. 354-360.

labours of the previous investigators of this subject, and of the grounds upon which their conclusions were based.

In the year 1702, De la Hire, who, according to Robins, was the first writer on the force of fired gunpowder, supposed that it was due to the increased elasticity of the air contained in and between the grains, the function of the powder itself being merely that of a heating agent. Robins (who, however, greatly underrated the temperature of explosion) pointed out that the elasticity so acquired would not exceed 5 atmospheres, and that such a pressure was not the two-hundredth part of the effort necessary to produce the observed effects.

Robins,* in 1743, read before the Royal Society a paper, in which he described experiments tending to show that gunpowder, when fired, generated permanent gases which, at ordinary temperatures and atmospheric pressure, occupied a volume 236 times greater than that of the unexploded powder. He made further experiments to show that, at the temperature which he conceived to be that of explosion, the elasticity of the permanent gases would be increased fourfold, and hence the maximum pressure due to fired gunpowder would be about 1000 atmospheres.

Robins considered that the whole of the powder (such as he employed) was fired before the bullet was sensibly moved from its seat. He argued that, were such not the case, a much greater effect would be realised from the powder when the weight of the bullet was doubled, trebled, etc.; but his experiments showed that in all these cases the work done by the powder was nearly the same.

In 1778, Dr Hutton,† of Newcastle-on-Tyne, read before the Royal Society an account of his celebrated researches in gunnery; and in his 37th tract are detailed the experiments from which he deduced the maximum pressure of gunpowder to be about twice that given by Robins, or a little more than 2000 atmospheres.

Hutton, like Robins, saw that the moving force of gunpowder was due to the elasticity of the highly-heated gases produced by explosion; and, upon the assumption that the powder was instantaneously ignited, he gave formulæ for deducing the pressure of the gas and velocity of the projectile at any point of the bore. These formulæ, the principles of thermodynamics being then unknown, are erroneous, no account being taken of the loss of temperature due to

* *New Principles of Gunnery*, 1805, pp. 59-74.

† *Mathematical Tracts*, 1812, vol. iii. pp. 209-316.

work performed; but we shall have occasion to point out that the error arising from this cause is not nearly so great as might be at first supposed.*

In 1797, Count Rumford † communicated to the Royal Society his experimental determinations of the pressure of fired gunpowder; his results, although conjecturally corrected by more than one writer, have retained up to the present time their position as the standard, if not the only, series of experiments in which the pressure has been obtained by direct observation.

In prosecuting his remarkable experiments Count Rumford had two objects in view: *first*, to ascertain the force exerted by explosive powder when it completely filled the space in which it was exploded; *secondly*, to determine the relation between the density of the gases and the tension.

The apparatus (see Fig. 1, p. 54) used by Rumford consisted of a small, strong wrought-iron vessel or chamber 0·25 inch (6·3 mm.) in diameter, and containing a volume of ·0897 cubic inch (1·47 c.c.). It was terminated at one end by a small closed vent filled with powder, so arranged that the charge could be fired by the application of a red-hot ball; at the other end it was closed by a hemisphere upon which any required weight could be placed.

When an experiment was to be made, a given charge was placed in the vessel, and a weight, considered equivalent to the resulting gaseous pressure, was applied to the hemisphere. If, on firing, the weight was lifted, it was gradually increased until it was just sufficient to confine the products of explosion, and the gaseous pressure was calculated from the weight found necessary.

The powder experimented with was sporting, of very fine grain; and as it contained only 67 per cent. nitre, it differed considerably from ordinary powder. Its specific gravity (1·868) and gravimetric density (1·08) were also very high; but in his experiments Count Rumford appears to have arranged so that the weight of a given volume of gunpowder was nearly exactly equal to that of the same volume of water—that is to say, the gravimetric density was about equal to unity.

* Hutton, in a note to the new edition of Robins's *Gunnery*, published in 1805, mentions that the elastic force of gunpowder was considered by John Bernoulli to be that of 100 atmospheres, while Daniel Bernoulli considered it to be equal to about 10,000 atmospheres.—Robins, *loc. cit.* p. 57.

† *Philosophical Transactions*, 1797, p. 222.

The curve drawn on Plate IX., p. 230 exhibits the results, of the first and most reliable series of Count Rumford's observations. It shows the relation he believed to exist between the density of the gas and its pressure, and is expressed by the empirical formula $p = 1{\cdot}841x^{1+{\cdot}0004x}$, p being the tension and x the density of the gas.

The charges with which Rumford experimented were very small; the largest, with one exception (by which his vessel was destroyed), was 18 grains (1·17 grm.). The total quantity of powder required to fill the vessel was about 28 grains (1·81 grm.). It may be observed that, if the curve (Plate IX.) were supposed to be true up to the point when the chamber is completely filled, the pressure exhibited would be about 29,000 atmospheres. But, high as this result is, Rumford considered it much below the truth. In addition to the series the results of which are graphically represented, a second series was made, the results of which were very discordant.

From Plate IX. it will be observed that, with a charge of 12 grains (0·78 grm.) (equivalent to a mean density in the products of combustion of 0·428), the tension of the gas was in the first experiment about 2700 atmospheres; but in this second series the tension with the same charge was repeatedly found higher than 9000 atmospheres.

The discrepancies between the two series of experiments are not explained; but, relying upon the second series, and on the experiment by which the cylinder was destroyed, Rumford calculated that the tension of exploded gunpowder, such as that employed by him when filling completely the space in which it is confined, is 101,021 atmospheres (662 tons on the square inch).* He accounts for this enormous pressure by ascribing it to the elasticity of the steam contained in the gunpowder, the tension of which he estimates as being doubled by every addition of temperature equal to 30° Fahr. He further considers the combustion of powder in artillery and small arms to be comparatively slow, and that hence the initial tension he assumes is, in their case, not realised.

In 1823, Gay-Lussac appears to have communicated to the "Comité des Poudres et Salpêtres" a report of his experiments upon the decomposition of gunpowder.† Gay-Lussac's products were obtained by allowing small quantities of gunpowder to fall into a tube

* Rumford, *loc. cit.* p. 280.

† We have been unable to obtain the original of this report; see, however, Piobert, *loc. cit.* p. 293.

arranged to receive the gases, and heated to redness. The collected permanent gases, when analysed, gave in 100 volumes 52·6 volumes of carbonic anhydride, 5 of carbonic oxide, and 42·4 of nitrogen. Gay-Lussac gave the volume of these gases, at a temperature of 0° Cent. and 760 mm. barometric pressure, as occupying 450 times the space filled by the powder, the gravimetric density of which was ·9. Piobert, however, points out that Gay-Lussac's results, thus stated, are not possible, and suggests that, by an error, the quantity of gas actually found has been doubled.

Piobert's suggestion is, from various corroborative circumstances, exceedingly probable, and is confirmed by the fact that Gay-Lussac himself estimated the permanent gases at about 250 volumes.

In 1825, Chevreul,* after drawing attention to the difference in the decomposition of gunpowder when occurring explosively, as in the bore of a gun, and when taking place slowly, as by ignition in open air, supposes the decomposition in the former case to be represented by the equation

$$2KNO_3 + S + C_3 = K_2S + N_2 + 3CO_2$$

He points out that the actual constituents of gunpowder are employed in proportions almost in exact accordance with this formula; and the same view appears to have been taken by Graham,† who further supposes that the potassium sulphide is converted into sulphate on coming into contact with the air.

Chevreul gives potassium sulphide, sulphate, carbonate, cyanide, nitrate or hyponitrite, and carbon as composing the solid residue of gunpowder when burnt slowly; and gives further, as the result of some experiments of his own, for the gaseous products in 100 volumes:—

Carbonic anhydride . .	45·41	vols.
Nitrogen	37·53	„
Nitrous oxide . . .	8·10	„
Sulph. hydrogen . . .	0·59	„
Marsh-gas	3·50	„
Carbonic oxide . . .	4·87	„

Between the years 1831-36 a great number of very important experiments, chiefly upon the combustion and inflammation of gunpowder, were made by General Piobert. The results of these experi-

* *Dictionnaire des Sciences Naturelles*, tom. xxxv. p. 58.
† *Encyclopædia Britannica*, Art. "Gunpowder."

ments, together with Piobert's theoretical views, are contained in his work on the properties and effects of gunpowder.*

Piobert considered that the velocity of inflammation of gunpowder, that is, the transmission of the ignition from one grain to another when the charge was contained in a close vessel or tube offering a high resistance, was very great; but he did not † consider that the influence of the high temperature and great tension of the gases exercised a sensible effect in increasing the rapidity of combustion of the individual grains.

It is somewhat difficult to collect his views upon the subject of the decomposition of gunpowder; and his work on this point must be taken more as a *résumé* of the views of chemists on the subject than as an expression of his own. He seems, however, to have ascribed a great influence to the mode of ignition, even on the quantity of permanent gases, and quotes results varying from 200 volumes to 650 volumes,‡ all taken at atmospheric temperatures and pressure.

He states that, from theory,§ the quantity of gas should be comprised between 330 and 350 volumes, and should amount in weight to three-fifths of that of the powder.

As regards the tension of the products at the moment of explosion, he accepts as tolerably correct the first series of Rumford's experiments, and makes the pressure of gunpowder, when fired in its own space, about 23,000 atmospheres.‖

He further considers it possible that the presence ¶ of the vapour of water may add to the explosive force of gunpowder. He shares Rumford's views as to the solid products being in a state of vapour at the moment of explosion; he ascribes the high tension he assumes to the difference in the behaviour of vapours and permanent gases when highly heated, and divides the phenomenon of explosion into two very distinct epochs:—the first when the solid products are in the state of elastic vapours, adding their tension to that of the permanent gases; the second epoch being when the permanent gases act alone, the vapours being condensed.

In 1843, General Cavalli ** proposed to apply to an experimental gun, at various distances from the bottom of the bore, a series of small barrels of wrought iron, arranged to throw a spherical bullet

* Piobert, G., *Traité d'Artillerie, Propriétés et Effets de la Poudre*, 1859.
† *Loc. cit.* pp. 158-162. ‡ *Loc. cit.* p. 292.
§ *Loc. cit.* p. 291. ‖ *Loc. cit.* pp. 357, 359. ¶ *Loc. cit.* p. 316.
** *Revue de Technologie Militaire*, tom. ii. p. 147.

which would be acted upon by the charge of the gun while giving motion to its projectile. By ascertaining the velocities of these bullets, Cavalli considered that the tensions in the bore would be ascertained. This arrangement was carried out with a "cannon de 16," under his own superintendence, in 1845; and from these experiments was deduced the theoretical thickness of the metal at various points along the bore.

General Cavalli appears to have estimated at a very high rate the tensions realised in the bores of guns. He * considered that, with the Belgian "brisante" powder of 1850, a tension of 24,000 atmospheres (158 tons per square inch) was actually realised, while in the less inflammable powders the tension was, he considered, under 4000 atmospheres.

In 1854, a Prussian Artillery Committee made a series of experiments † to determine the pressure exerted by the powder in the bores of the 6- and 12-pr. smooth-bored guns.

The plan adopted was a great improvement on that suggested by Cavalli, and was as follows:—

In the powder-chamber a hole was drilled, and in this hole was fitted a small gun-barrel of a length of, say, 8 inches. Now, if the gun be loaded, and if in the small side barrel we place a cylinder whose longitudinal section is the same as that of the projectile, when the gun is fired, on the assumption that the pressure in the powder-chamber is uniform, the cylinder and the projectile will in equal times describe equal spaces, and after the cylinder has travelled 8 inches it will be withdrawn from the action of the charge. If, then, we know the velocity of the cylinder, we know that of the projectile when it has travelled 8 inches. Again, if we make the section of the cylinder half that of the projectile, it will describe in the same time double the space and have acquired double the velocity, and so on; so that, for example, if the section of the cylinder be one-eighth of that of the projectile, we shall, if we know the cylinder's velocity, know that of the projectile when it has travelled 1 inch.

The general results at which the Prussian Committee arrived were, that in the 6-prs. the maximum pressure realised was about 1100 atmospheres (7·2 tons per square inch), and in the 12-prs. about 1300 atmospheres (8·5 tons per square inch). They further found

* Cavalli, Gen., *Mémoire sur les Eclatements des Canons, &c.*, 1867, p. 83.

† *Archiv für die Offiziere der Königlich Preussischen Artillerie- und Ingenieur-Corps*, tom. xxxiv. p. 2. *Revue de Technologie Militaire*, tom. i. p. 9, tom. ii. p. 152.

that, with every charge with which they experimented, two maxima of tension were distinctly perceptible.

These experiments were made the subject of an elaborate memoir by the distinguished Russian artillerist General Mayevski,* who confirmed generally the results arrived at by the Prussian Committee.

Between the years 1857 and 1859, Major Rodman † made an extensive series of experiments on gunpowder for the United States Government.

The chief objects of Rodman's experiments were,—1st, to ascertain the pressure exerted on the bores of their then service guns; 2nd, to determine the pressures in guns of different calibres, the charges and projectiles in each calibre being so arranged that an equal column or weight of powder was behind an equal column or weight of shot; 3rd, to investigate the effect produced on the gaseous tension in the bore of a gun by an increment in the size of the grains of the powder; and 4th, to determine the ratio which the tension of fired gunpowder bore to its density.

In carrying out these experiments, Rodman made use of an instrument devised by himself, and since extensively used on the Continent. It is represented in Plate X., Fig. 1 (p. 230), and consists of a cylinder, A, communicating by a passage, B, with the bore of the gun or interior of the vessel, the pressure existing in which it is desired to measure.

In the cylinder is fitted the indicating-apparatus, consisting of a piece of copper, C, against which is placed the knife D, shown in elevation and section. The pressure of the gas acting on the base of the piston E causes the indenting-tool to make a cut on the soft copper, and, by mechanical means, the pressure necessary to make a similar cut in the copper can be determined.

A small cup at F prevents any gas passing the indenting-tool, while the little channel G allows escape should any, by chance, pass.

Rodman considered that his experiments showed that the velocities obtained in large guns with the service small-grained powder might be obtained, with a greatly diminished strain on the gun, by the use of powder properly adapted in size of grain to the calibre and length of bore proposed to be used.

Rodman's conclusions on this head are extremely valuable,

* *Revue de Technologie Militaire*, tom. ii. p. 174.

† *Experiments on Metal for Cannon and qualities of Cannon Powder.* Boston, 1861.

although, as has been elsewhere pointed out,* some of his experimental results are open to grave criticism. His experiments on the relation between the tension and density of powder (the powder being placed in a strong shell and fired through a small vent) were not carried far enough to be of much value; but on Plate IX., Fig. 2 (p. 230), we have represented his results in comparison with those of Rumford.

Rodman also made an attempt to determine the pressure that would be exerted when powder was exploded in its own space. He fired the charges, as before, through a vent in a strong shell, and considered that the maximum pressure would be realised before the shell burst. His results were very various, ranging from 4900 to 12,400 atmospheres, the highest tension being obtained with the smallest charge. These anomalous results were probably due to the distance from the charge at which his instrument was placed, the products of combustion doubtless attaining a very high velocity before acting on the piston.

In 1857, Bunsen and Schischkoff published† their very important researches on gunpowder. Their experiments were directed, first, to determine the nature and proportions of the permanent gases generated by the explosion of gunpowder; secondly, to determine the amount of heat generated by the transformation. With the aid of these experimental data they deduced, from theoretical considerations, the temperature of explosion, the maximum pressure in a close chamber, and the total theoretical work which gunpowder is capable of performing on a projectile.

The powder in these experiments was not exploded, but deflagrated, by being allowed to fall in an attenuated stream into a heated bulb, in which, and in the tubes connected with it, the products were collected.

The transformation, according to these experimenters, experienced by gunpowder in exploding, is shown in the following scheme. It will be observed that the permanent gases represented only about 31 per cent. of the weight of the powder, and occupied at 0° Cent. and 760 mm. only 193 c.c.—that is, approximately, 193 times the volume occupied by the unexploded powder.

* Noble, "Tension of Fired Gunpowder," *Proc. Royal Institution*, vol. vi. p. 282; also see *ante*, p. 60.

† Poggendorff's *Annalen*, vol. cii. p. 325. A translation of Bunsen and Schischkoff's memoir appeared in the occasional papers of the Royal Artillery Institution, vol. i. p. 297; see also, at p. 312 of the same volume, Mr Abel's remarks on Bunsen and Schischkoff's results.

TABLE 1.—*Showing the transformation experienced by gunpowder after Bunsen and Schischkoff.*

1 grm. powder		
Nitre		·7899
Sulphur		·0984
Charcoal	C	·0769
	H	·0041
	O	·0307

Gave when exploded

	grm.		grm.
Residue	0·6806	K_2CO_3	·1264
		$K_2S_2O_3$	·0327
		K_2SO_4	·4227
		K_2S	·0213
		KCNS	·0030
		KNO_3	·0372
		$(NH_4)_2CO_3$	·0286
		S	·0014
		C	·0073

			grm.	c.c.
Gases	0·3138	SH_2	·0018	= 1·16
		O	·0014	= 1·00
		CO	·0094	= 7·49
	0·9944	CO_2	·2012	= 101·71
		H	·0002	= 2·34
		N	·0998	= 79·40
				193·10

In Table 3 a comparative statement is given of the foregoing results with those of other recent experimenters, and with those furnished by our investigations. (See p. 130.)

Bunsen and Schischkoff determined the number of units of heat generated by combustion, by exploding a small charge of powder in a tube immersed in water. They found that the combustion of a gramme of powder gave rise to 620 gramme-units of heat; and hence they calculated that the temperature of explosion, in a close chamber impervious to heat, was 3340° Cent. (5980° Fahr.).

From the above data the pressure in a close vessel is deducible; and they computed that the maximum pressure which the gas can attain, which it may approximate to but can never reach, is about 4374 atmospheres, or 29 tons on the square inch.

Bunsen and Schischkoff further computed the total theoretical work which a kilog. of gunpowder is capable of producing on a projectile at 67,400 kilogrammetres.

In the course of our paper we shall have frequent occasion to refer to these very important researches.

In 1858, D. J. Linck* repeated, with Wurtemburg war-powder, Bunsen and Schischkoff analysis of the products of combustion, which were obtained by the same method. The composition of the powder used is given in Table 2, p. 128.

Linck's results, which we have placed in the same Table as those of Bunsen and Schischkoff, differed in several points from the results of the latter chemists, but chiefly in the much smaller quantity of

* *Annalen der Chemie*, vol. cix. p. 53.

potassium sulphate found. Linck considered that 1 grm. of the powder used generated 218·3 c.c. of gas.

In 1863, M. von Karolyi * examined the products of combustion of Austrian musket- and ordnance-powder.

M. von Karolyi's method of obtaining the products of combustion consisted in suspending in a spherical shell a small case containing a charge of the powder to be experimented with. Before firing the charge, the air contained in the shell was exhausted; the powder was fired by electricity.

The arrangement will readily be understood from the sketch shown in Fig. 3, Plate XI. (p. 230).

After combustion, the gases were obtained for examination by means of the stop-cock, while the solid residue remaining in the shell was removed with water and filtered.

The composition of the powders used is given in Table 2 (p. 128), and the results of analysis in Table 3, p. 130. Von Karolyi computed that the gases resulting from 1 grm. of small-arm powder generated 226·6 c.c., and from 1 grm. of ordnance-powder 200·9.

The Astronomer Royal, Sir G. B. Airy, in a paper † published in 1863, "On the Numerical Expression of the Destructive Energy in the Explosions of Steam-boilers, and on its comparison with the Destructive Energy of Gunpowder," considers that "the destructive energy of 1 cubic foot of water (62·23 lbs. = 28·23 kilogs.) at the temperature which produces the pressure of 60 lbs. to the square inch is equal to that of 1 lb. of gunpowder, and that the destructive energy of 1 cubic foot of water at the temperature which produces the pressure of 60 lbs. to the square inch, surrounded by hot iron, is precisely equal to the destructive energy of 2 lbs. of gunpowder as fired in a cannon."

Airy takes the energy of a kilog. of powder as fired from a gun at 56,656 kilog. metres = 82·894 foot-tons per lb. of powder; so that the total energy of gunpowder would be somewhat less than double the above value. He states, however, that this estimate does not pretend to be very accurate.

In 1869 were published, in the *Zeitschrift für Chemie*,‡ the results of some experiments made by Colonel Fedorow to determine whether the products varied materially with the mode of combustion.

Fedorow experimented (1) by firing a pistol with a blank charge

* Poggendorff's *Annalen*, April 1863. *Philosophical Magazine*, ser. 4, vol. xxvi. p. 266.

† *Philosophical Magazine*, ser. 4, vol. xxvi. p. 329. ‡ *Ibid.* vol. v. p. 12.

into a glass tube 4 feet long, (2) and by firing a shotted 9-pr. bronze gun with 3 lbs. of powder; the residues were in each case dissolved in water and analysed.

The composition of the powder employed by Fedorow is given in Table 2, and his analytical results are shown in Table 3.

From the experiments with the gun, Fedorow calculated that the gaseous products were 82·6 c.c. N, 162·1 c.c. CO_2, and 14 c.c. SO_2 and O. He considers that several successive reactions take place during combustion, that potassium sulphate and carbonic anhydride are first formed, while the excess of carbon reduces the sulphate to carbonate, hyposulphite, and carbonic anhydride.

In 1871, Captain Noble,* one of the present writers, in detailing to the Royal Institution his earlier researches on the tension of fired gunpowder, stated that the conclusion at which he had arrived from the results of his experiments, where the products of combustion were entirely or partially confined, was, that the maximum pressure of fired gunpowder, of the usual gravimetric density, when unrelieved by expansion, did not greatly exceed 6100 atmospheres (40 tons to the square inch). Upon the same occasion a curve was exhibited, showing the relation between the tension and the density of the exploded products. These results have been confirmed by our present more extensive and exact investigations.

Captain Noble also stated that, by means of a special apparatus which was fully described at the time, he had not only determined the tension of the gases at various densities, but had exploded considerable charges filling entirely the chambers of close vessels, and had altogether retained and at pleasure discharged the gaseous and other products of combustion.†

Berthelot‡ published, in 1872, a collection of theoretical papers upon the force of powder and other explosive substances.

Berthelot does not attempt to evaluate the force of fired gunpowder, but evidently accepts as tolerably correct§ the tensions assigned by Rumford and Piobert, and accounts for the discrepancy

* *Proceedings of Royal Institution*, vol. vi. p. 282. *Revue Scientifique*, No. 48, p. 1125.

† In the present paper, in Section K, the results of some of Capt. Noble's earlier experiments are given. They accord, as will be seen, exceedingly well with the series we have discussed at length; but a few experiments made with a fine-grained powder are excluded, both because the powder, being sporting, was not comparable with the fine-grain used in the present researches, and because the differences in their composition are unknown, the sporting-powder not having been analysed.

‡ *Sur la Force de la Poudre.* Paris, 1872.

§ *Loc. cit.* p. 80.

between their conclusions and those of the modern chemists by assuming that the laws of Mariotte and Gay-Lussac lose all physical significance for pressures so enormous as those developed in the combustion of gunpowder.

Berthelot is disposed * to think that dissociation plays a considerable rôle during the expansion of the products in the bore of a gun. He supposes that the phenomena of dissociation do not exercise their influence only during the period of maximum effect, but that, during the expansion of the gases, a cooling effect is produced, by which a more complete combination is effected and more heat disengaged.

Taking Bunsen and Schischkoff's experiments as a basis, Berthelot expresses the decomposition experienced by gunpowder by the equation †

$$16KNO_3 + 6S + 13C = 5K_2SO_4 + 2K_2CO_3 + K_2S + 16N + 11CO_2$$

which he considers represents their results with sufficient exactness.

In 1873, M. de Tromenec ‡ communicated to the Academy of Sciences a short memoir on the means of comparing the absolute force of varieties of powder. His method was based upon the principle that, when a body is exploded without producing mechanical effect, the "force disponible" is converted into heat, and that it is only necessary to explode a given weight in a close vessel and determine the heat produced.

The apparatus used by De Tromenec was closed in much the same manner as was that employed by Captain Noble in his earlier experiments already alluded to. The three kinds of powder experimented with gave results varying between 729 and 891 calories generated by the combustion of 1 kilog. of powder.

In the same § number of the *Comptes Rendus* in which De Tromenec's memoir is given, appears a note by MM. Roux and Sarrau, in which, and in a subsequent note,|| are determined, with small charges, some of the points to which our own investigations have been specially directed.

MM. Roux and Sarrau have given, for five species of powder, the number of calories and volume of gas generated by a given weight of powder, and have from these data calculated the temperature of combustion and tension of the gas.

With one of the powders, representing closely the composition of those chiefly experimented with by us, the number of calories and

* *Sur la Force de la Poudre*, p. 83.
† *Loc. cit.* p. 91.
‡ *Comptes Rendus de l'Académie des Sciences*, tom. lxxvii. p. 126.
§ *Comptes Rendus*, tom. lxxvii. p. 138.
|| *Ibid.* p. 478.

volume of the gas agree nearly exactly with the numbers found by ourselves. There is, however, a considerable difference in our determinations (both theoretical and experimental) of the tension of the gas and also of the temperature of explosion, the temperature being estimated by Roux and Sarrau at about 4200° Cent., and the tension at about 4700 atmospheres.

We shall return, however, to these points when discussing our own experiments.

(*b*) OBJECTS OF EXPERIMENTS.

The chief objects which we had in view in making these investigations were:—

First. To ascertain the products of combustion of gunpowder fired under circumstances similar to those which exist when it is exploded in guns or mines.

Second. To ascertain the tension of the products of combustion at the moment of explosion, and to determine the law according to which the tension varies with the gravimetric density of the powder.

Third. To ascertain whether any, and, if so, what well-defined variation in the nature or proportions of the products accompanies a change in the density or size of grains of the powder.

Fourth. To determine whether any, and, if so, what influence is exerted on the nature of the metamorphosis by the pressure under which the gunpowder is fired.

Fifth. To determine the volume of permanent gases liberated by the explosion.

Sixth. To compare the explosion of gunpowder fired in a close vessel with that of similar gunpowder when fired in the bore of a gun.

Seventh. To determine the heat generated by the combustion of gunpowder, and thence to deduce the temperature at the instant of explosion.

Eighth. To determine the work which gunpowder is capable of performing on a shot in the bore of a gun, and thence to ascertain the total theoretical work, if the bore be supposed of indefinite length.

(*c*) METHODS OF EXPERIMENT.

1. *Explosion-apparatus.*

We propose, in the first place, to describe the principal apparatus used in these investigations, and shall commence with that portion

which is of primary importance, viz., the vessel in which the explosions were produced. Two sizes of vessels were used, the larger being capable of holding about $2\frac{1}{4}$ lbs. (1 kilog.) of powder, the other being about half that capacity.

Both vessels were of the same general construction, and similar to that described in Captain Noble's Lecture at the Royal Institution already referred to. A drawing of the apparatus is given in Plate X., Figs. 2 and 3 (p. 230).

A (see Figs. 2 and 3) is a mild steel vessel of great strength, carefully tempered in oil, in the chamber of which (B) the charge to be exploded is placed.

The main orifice of the chamber is closed by a screwed plug (C), called the firing-plug, which is fitted and ground into its place with great exactness.

In the firing-plug itself is a conical hole, which is stopped by the plug D, also ground into its place with great accuracy. As the firing-plug is generally placed on the top of the cylinder, and as, before firing, the conical plug would drop into the chamber if not held, it is retained in position by means of the set-screw S, between which and the cylinder a small washer (W) of ebonite is placed. After firing, the cone is, of course, firmly held, and the only effect of internal pressure is more completely to seal the aperture. At E is the arrangement for letting the gases escape; the small hole F communicates with the chamber where the powder is fired, and perfect tightness is secured by means of the mitred surface G. When it is wished to let the gases escape, the screw E is slightly withdrawn, and the gas passes into the passage H.

At K is placed the "crusher-apparatus" for determining the tension at the moment of explosion.

When it is desired to explode a charge, the crusher-apparatus, after due preparation, is first carefully screwed into its place, and the hole F closed. The cone in the firing-plug is covered with the finest tissue-paper, to act as an insulator.

The two wires LL, one in the insulated cone, the other in the cylinder, are connected by a very fine platinum wire passing through a small glass tube filled with mealed powder. Upon completing connection with a Daniell's battery, the charge is fired.

The only audible indication of the explosion is a slight click; but frequently, upon approaching the nose to the apparatus, a faint smell of sulphuretted hydrogen is perceptible.

The difficulties we have met with in using this apparatus are more serious than might at first sight appear.

In the first place, the dangerous nature of these experiments rendered the greatest caution necessary, while, as regards the retention of the products, the application of contrivances of well-known efficacy for closing the joints, such as *papier-mâché* wads between discs of metal (a method which has been successfully employed with guns), are inadmissible, because the destruction of the closing or cementing material used, by the heat, would obviously affect the composition of the gas. Every operation connected with the preparation of the apparatus for an experiment has to be conducted with the most scrupulous care. Should any of the screws not be perfectly home, so that no appreciable amount of gas can escape, the gases, instantly upon their generation, will either cut a way out for themselves, escaping with the violence of an explosion, or will blow out the part improperly secured, in either case destroying the apparatus.

The effect produced upon the apparatus, when the gas has escaped by cutting a passage for itself, is very curious. If, for example, one of the plugs has not been sufficiently screwed home, so that the products of combustion escape between the male and female threads, the whole of these threads at the point of escape present the appearance of being washed away, the metal having been evidently in a state of fusion, and carried over the surface of the plug by the rush of the highly-heated products.

Again, the difficulty of opening the vessel after explosion, when large charges have been used, is very great. This will be readily understood when the temperature and pressure of explosion are considered. The exploding-chamber being filled with products intensely heated and under an enormous pressure, there is an expansion of the interior surface of the cylinder. Hence small portions of the fluid products become forced in between the threads of the screws. These solidify into a substance of intense hardness, which cements together the metal surfaces, and, on cooling, the contraction of the cylinder puts such a pressure on the screw, that, in attempting to open it, seizure is very difficult to avoid. In one or two cases it was found impossible to open the cylinder until melted iron had been run round it, so as to cause it to expand.

This difficulty has been in a great measure avoided, in the more recent experiments, by making the screws conical, so that

when once started clearance is rapidly given, and they are removed with comparative ease.

2. *Measurement of Pressure.*

The apparatus used for the measurement of the tension of the gas was precisely similar to that which has been used by the Committee on Explosives, and consists of a screw-plug of steel (Plate X., Figs. 4 and 5, p. 230), which admits of a cylinder of copper or other material (A) being placed in the small chamber (B). The entrance to the chamber is closed by the movable piston (C), and the admission of the gas is prevented by the use of the gas-check (D). When the powder is fired, the gas acts upon the base of the piston and compresses the cylinder. The amount of compression of the cylinder serves as an index to the force exerted, the relation between the amount of crush and the pressure necessary to produce it being previously carefully determined.

3. *Measurement of the Volume of the Permanent Gases.*

The apparatus used for the measurement of the permanent gases is shown in Plate XI., Figs. 1 and 2 (p. 230). A is a vessel the annular space (B) of which is filled with water; on the surface of this a thin film of oil is floated, to prevent any slight absorption of the gas which might otherwise take place.

Immediately after the explosion of a charge, the gas from which it is desired to measure, the cylinder (C) containing the products is placed on the table (D), and the gasometer (E) is placed over the cylinder; the height of the water on the glass scale (F) being then registered, the escape-screw (G) of the cylinder is turned, by means of a turn-cock passing through the stuffing-box (M).

When the gas has all escaped, the height indicated on the glass scale being again registered, the cubic contents are known, and the thermometer (H) and height of barometer being noted, the necessary data are available for reducing the volume of the gas to a temperature of 0° Cent. and a barometric pressure of 760 mm.

4. *Measurement of Heat.*

To determine the heat generated by explosion, a charge of powder was weighed and placed in one of the smaller cylinders described, which was kept for some hours in a room of very uniform tempera-

ture. When the apparatus was throughout of the same temperature, the thermometer was read, the cylinder closed, and the charge exploded.

Immediately after explosion the cylinder was placed in a calorimeter containing a given weight of water at a measured temperature, the vessel being carefully protected from radiation, and its calorific value in water having been previously determined.

The uniform transmission of heat through the entire volume of water was maintained by agitation of the liquid, and the thermometer was read every five minutes until the maximum was reached. The observations were then continued for an equal time to determine the loss of heat in the calorimeter due to radiation, etc.; the amount so determined was added to the maximum temperature.

In this method there is a possible source of error; the walls of the cylinder being of very considerable thickness, it is obvious that, although the outer surface of the cylinder must be of the same temperature as the water, it by no means follows that this is true of the internal surface; consequently the loss of heat due to radiation, etc., may be in some degree compensated by a flow of heat from the interior.

We had reason, from some experiments we made, to believe that the error due to this cause was very small; and our views were confirmed by finding no appreciable rise of temperature on placing some water from the calorimeter into the chamber of the cylinder immediately after an experiment.

5. *Collection of Gaseous Products.*

To collect the gases for analysis, a small pipe was screwed into the escape-passage (H) of the cylinder (Plate X., Figs. 2 and 3, p. 230), and an indiarubber tube, terminating in a glass nozzle, was led to a mercurial trough. Before the gas was taken, a sufficient quantity was allowed to escape to clear the tubes of air; the gas was then collected in tubes over mercury, and confined in the usual manner by sealing them with the blowpipe.

The gas was generally collected in from five to fifteen minutes from the time of explosion. Owing to the dangerous nature of the experiments, and the precautions necessary to be adopted in exploding such considerable charges of powder, it was not generally possible to collect the gases more rapidly; but a comparison of the analysis of different tubes taken from the same experiment has shown that,

at all events within moderate limits, no change takes place in the composition of the gas by its continued contact with the solid products.

6. *Collection of Solid Products.*

The collection of the solid products presented much more difficulty than that of the gaseous products. On opening the cylinder, the whole of the solid products were found collected at the bottom, there being generally an exceedingly thin (in fact, with large charges, quite an inappreciable) deposit on the sides. Upon the firing-plug there was usually a button of deposit, which differed considerably both in appearance and in chemical composition from the rest. In the button a crystalline structure was quite apparent, some of the crystals being large and transparent. The surface of the deposit was generally perfectly smooth, and of a very dark grey, almost black, colour. This colour, however, was only superficial, and through the black could be perceived what was probably the real colour of the surface, a dark olive-green. The surface of the deposit, and the sides of the cylinders, had a somewhat greasy appearance, and were indeed greasy to the touch. On the smooth surface were frequently observed very minute particles, in appearance like soot, but of the greasy texture to which we have alluded.

The removal of the deposit was generally attended with great difficulty, as it formed an exceedingly hard and compact mass, which always had to be cut out with steel chisels. Lumps would frequently break off, but a considerable portion flew off before the chisel in fine dust. In various experiments, on examining the fracture as exhibited by the lumps, the variation in physical appearance was very striking, there being marked differences in colour, and also, frequently, a marked absence of homogeneity, patches of different colours being interspersed with the more uniform shade of the fracture. There was no appearance of general crystalline structure in the deposit; but, on examination with a microscope and sometimes with the naked eye, shining crystals of metallic lustre (sulphide of iron) were observed. On the whole, the general appearance of the deposit was attended with such considerable variations, that, for minute details, we must refer to the account of the experiments themselves. The deposit always smelt powerfully of sulphuretted hydrogen, and frequently strongly of ammonia. It was always exceedingly deliquescent, and after a short exposure to the air became black on the surface, gradually passing over into an inky-looking pasty mass. As in physical

appearance, so in behaviour of the solid, when removed from the cylinder, there were considerable differences between the experiments. The deposit was transferred to thoroughly dried and warm bottles, and sealed up as rapidly as possible. In most cases, during the very short time that elapsed while the transference was being made, no apparent change took place; but in some a great tendency to development of heat was apparent; and in one instance, in which a portion of the deposit (exhibiting this tendency in a high degree) was kept exposed to the action of the air, the rise of temperature was so great that the paper on which it was placed became charred, and the deposit itself changed colour with great rapidity, becoming a bright orange-yellow on the surface.

This tendency to heating always disappeared when the deposit was confined in a bottle and fresh access of air excluded.

The portion of the residue which could not be removed from the cylinder in a dry state was dissolved out with water, the solution being reserved for examination in well-closed bottles.

(*d*) ANALYSIS OF THE PRODUCTS OF EXPLOSION.

1. *Gaseous Products.*

The method pursued for the analysis of the gaseous products of explosion presented only one important point of difference from that pursued by Bunsen and Schischkoff. The volume of gas at command being more considerable than was the case in the investigations of those chemists, it was found more convenient to have recourse to methods for determining the sulphuretted hydrogen differing from that which they adopted—namely, its estimation by oxidation of the sulphur in the ball of potassium hydrate employed for absorbing the carbonic anhydride and sulphuretted hydrogen together. In some instances the volume of this gas was ascertained by absorption with manganese balls, but generally the following indirect method was pursued. The combined volume of carbonic anhydride and sulphuretted hydrogen was determined in one portion of the gas by means of potassium hydrate; another portion of gas was then treated with a small quantity of cupric sulphate, and the volume of carbonic anhydride determined in the gas thus freed from sulphuretted hydrogen.

The following numerical data relating to the analysis of the gases obtained by the explosion of 190·5 grms. of R. L. G. gunpowder (of

Waltham-Abbey manufacture) in five times its own space, are given in illustration of the detailed result obtained:—

I.

	Volume.	Temperature. °	Pressure.	Volume corrected for temperature and pressure.
1. Original volume of gas .	144·4	13·3	0·7243	99·80
2. After absorption of CO_2 and SH_2 . . .	78·2	13·3	0·6727	50·16
3. After absorption of oxygen	76·9	14·4	0·6795	49·64

II.

	Volume.	Temperature.	Pressure.	Volume corrected for temperature and pressure.
4. Volume of original gas after absorption of sulphuretted hydrogen . .	144·2	14·2	0·7293	99·97
5. After absorption of CO_2 .	82·2	16·3	0·6672	51·76
6. After absorption of oxygen	80·6	18·8	0·6735	50·79

III.

	Volume.	Temperature.	Pressure.	Volume corrected for temperature and pressure.
7. Portion of 3 transferred to eudiometer . . .	174·8	15·4	0·1983	32·81
8.*After addition of air .	248·4	15·5	0·2712	63·75
9. After addition of oxygen .	319·5	15·6	0·3427	103·58
10. After explosion with oxyhydrogen gas . .	310·8	15·8	0·3302	97·02
11. After absorption of CO_2 .	291·6	18·3	0·3271	89·39
12. Portion of 11 transferred to clean eudiometer .	301·5	18·6	0·3141	88·66
13. After addition of hydrogen	550·8	18·9	0·5642	290·85
14. After explosion (dry) .	416·0	18·8	0·4295	167·16

By calculation from the above data, the composition of this gas, in volumes per cent., was found to be as follows:—

Carbonic anhydride . . .	46·17
Sulphuretted hydrogen . .	3·91
Oxygen	0·52
Carbonic oxide	11·46
Marsh-gas	0·03
Hydrogen	2·72
Nitrogen	35·18

* Air was added to dilute the gas in this and one or two subsequent explosion experiments; but this precaution was found to be unnecessary, and was therefore not continued.

The gas in each experiment was generally collected in three or four large tubes. The contents in one tube sufficed, in most instances, for the complete analysis; but the results obtained were always controlled by determinations of several, if not of the whole, of the constituents in the contents of another tube. Only in one instance were the contents of different tubes, collected from one and the same experiment, found to differ materially in composition; in this particular instance the proportion of sulphuretted hydrogen in the different tubes was discordant. The mean of the results furnished by the contents of the three tubes was taken to represent the composition of the gas.

2. *Solid Residue.—Preparation of the Residue for Analysis.*

The residue, as collected for analysis, consisted of one or more large masses, besides a quantity in a more or less fine state of division which had been detached from the sides of the vessel. The appearance presented by the large pieces themselves indicated that they were by no means homogeneous, and they evidently differed in some respects from the smaller particles just referred to; moreover, the foreign matters (metal and glass) could not be expected to be uniformly distributed throughout the mass, and a chemical examination of the latter clearly indicated that certain constituents existed in different proportions in the upper and lower parts of the residue. For these reasons, in order to ensure the attainment of results correctly representing the composition of the residue, it appeared indispensable to operate upon the entire quantity at one time, with the view of determining the total amount of matter insoluble in water, and of preparing a solution of uniform composition in which the several components of the residue could be estimated. As the investigation proceeded, much inconvenience and delay were experienced from the necessity of working with very large quantities (from 400 to 100 grms.), which rendered the filtrations and washings protracted operations, and necessitated dealing with very large volumes of liquid. It was therefore attempted to expedite the examination of the residues by so preparing them that only portions might be operated upon at one time in conducting the individual determinations of the constituents. The impossibility of pulverising and mixing the residue by any ordinary mode of proceeding, on account of the rapidity with which oxygen and water were absorbed from the air, was demonstrated by two or three attempts. An

arrangement was therefore devised for performing the operation in an atmosphere of pure nitrogen. The gas employed was prepared in the following manner:—

A gasometer filled with air was submitted to a gentle pressure causing the air to flow very slowly through a delivery-pipe to a porcelain tube filled with copper turnings and raised to a red heat. To remove any traces of oxygen, the nitrogen passed from the tube through two Woulfe's bottles containing pyrogallic acid dissolved in a solution of potassium hydrate; and, finally, to remove moisture, it passed through two U-tubes filled with pumicestone moistened with sulphuric acid. The nitrogen thus obtained was collected in indiarubber bags; the residue was placed in a closed mill, connected by an indiarubber tube with the gas-bag, which was subjected to a considerable pressure to establish a plenum in the mill. The substance was then ground, and allowed to fall into bottles, which were at once sealed. By this treatment a sufficient degree of uniformity in different samples of any particular residue was generally attained; in some cases, however, the state of division of the substance was not sufficiently fine to secure such intimacy of mixture as would preclude the occurrence of discrepancies in the analytical results furnished by different samples. It was therefore found necessary to return occasionally to the employment of the entire residue obtained in one experiment for determining its composition.

3. *Analysis of the Solid Residue.*

Qualitative analysis indicated that the proportions of the following substances had to be determined in the solid residue.

a. Portion insoluble in water.—This consisted of steel (unavoidably detached from the interior of the vessel during removal of the residue) and of small quantities of other metals, besides glass, which were used in the construction of the electric igniting arrangement. The weight of these substances was deducted from the residue, as foreign to the research.

In addition to these substances, the residue insoluble in water contained generally traces of charcoal, besides sulphur, which was combined with iron and portions of the other metals, and the amount of which is included in the statement of results as *free sulphur*, together with the proportion which was found, in combination with potassium, in excess of the amount required to form the monosulphide.

b. Portion soluble in water.—In this, the chief portion of the residue, there existed the potassium sulphide, sulphocyanate, hyposulphite, sulphate, carbonate, and nitrate, besides ammonium carbonate, and, in very exceptional cases, potassium hydrate. The estimation of the proportions in which these several constituents existed in the residue was conducted as follows:—

c. Water contained in the residue.—It is obvious that the highly hygroscopic nature of the powder-residue rendered it impossible to transfer the product of an explosion from the iron cylinder to suitable receptacles for its preservation out of contact with the atmosphere without some absorption of moisture, however expeditiously the operation was performed. Moreover, any water produced during the explosion, or pre-existing in the powder, would necessarily be retained by the solid residue after explosion, as the gas remained in contact with a large surface of this powerful desiccating agent for some time before it could be collected. In some instances the water was expelled from the residue by exposing it for some time to a slow current of hydrogen at 300° Cent., the gas and volatile matters being passed into solution of lead acetate, for the purpose of retaining sulphur, and the weight of the dried residue determined. The amount of residue, however, was generally too considerable for this operation to be satisfactorily performed; there was therefore no alternative in such cases but to assume that the difference between the total weight of the residue and the combined weights of its several solid constituents, ascertained in almost every instance by duplicate and check determinations, represented the amount of water present in the substance.*

d. Separation of the portion insoluble in water, and determination of sulphur in it.—The separation was accomplished by thoroughly washing the entire residue, or about 7 grms. of the ground residue, with well-boiled water until no discoloration was produced in the washings by lead acetate. Boiled water was employed to avoid oxidation of any of the constituents. After drying and washing the residue, it was introduced, with its filter, into a small flask; a little potassium bichromate was added before addition of nitric acid, to guard against violent reaction and the possibility of minute quantities of sulphur escaping as sulphuretted hydrogen. The oxidation was completed by the addition of potassium chlorate; the liquid, after

* If discrepancies existed between the results of determination of the several constituents and the check-determinations, the water was estimated, as described, in a portion of the residue.

sufficient dilution, was filtered and evaporated, the residue redissolved in water, with addition of chlorhydric acid, and the sulphuric acid determined in the solution by the usual method.

The *proportion of charcoal* contained in the insoluble residue was, in most instances, so small that no importance could be attached to any attempt to determine the quantity. In a few cases its amount was determined by combustion.

e. Potassium monosulphide.—The method pursued differed but very slightly from that adopted by Bunsen and Schischkoff. The aqueous solution, separated from the insoluble portion, was digested with pure ignited cupric oxide in a well-closed flask, with occasional agitation, until it became colourless. The oxide containing sulphide was then filtered off, thoroughly washed, and the sulphur was determined in it by oxidation according to the method just described (*d*).

f. Potassium sulphate.—The filtrate obtained after the treatment with cupric oxide just described (or a measured quantity of it, if the entire residue was operated upon at one time) was mixed with chlorhydric acid and boiled to expel the sulphurous acid resulting from the decomposition of hyposulphite; the liquid was then separated by filtration from liberated sulphur, and the sulphuric acid determined as barium sulphate.

g. Potassium hyposulphite.—The solution obtained by treatment, as above described, of about 4 grms. of the residue (or a sufficient volume prepared from the entire residue) was acidulated with acetic acid; 3 or 4 c.c. of starch solution were added, and the hyposulphurous acid determined by means of a standard iodine solution.

h. Potassium sulphocyanate.—A solution of the residue, after separation of the insoluble portion and the soluble sulphide, was carefully acidified with a measured quantity of dilute chlorhydric acid, so as to avoid separation of sulphur. The oxidation of the hyposulphite was then effected by the gradual addition of a very dilute solution of ferric chloride until the liquid exhibited a permanent pink tint. A measured quantity of the ferric solution was afterwards gradually added until the greatest attainable depth of colour was produced. To determine what was the amount of sulphocyanate thus arrived at, a volume of water corresponding to that of the original solution tested was mixed with equal volumes of the dilute chlorhydric acid and ferric chloride to those used in the previous experiments. A solution of potassium sulpho-

cyanate of known strength was then gradually added until a depth of colour corresponding to that of the actual assay was produced.

i. Potassium carbonate.—After the usual treatment of a solution of the residue with cupric oxide, pure manganous sulphate or chloride was added to the liquid in excess; the resulting precipitate might generally be washed by decantation in the first instance; after complete washing it was transferred to a small flask suitably fitted for the liberation of carbonic anhydride from it, by addition of sulphuric acid, and for the transmission of the gas through small weighed absorption-tubes containing respectively sulphuric acid, calcium chloride, and solution of potassium hydrate. The increase in weight of the latter corresponded to the proportion of carbonic anhydride in the solid residue.

j. Potassium sulphide, potassium carbonate, and potassium hydrate.—Pure manganous chloride or sulphate was added in excess to the aqueous solution of the residue, and the amount of manganese, in the thoroughly washed precipitate, determined as red oxide. If the amount obtained exceeded those which would be furnished by the potassium sulphide and carbonate (deduced from the previous determinations), the excess was taken to correspond to potassium hydrate existing in the residue. If it was less, the sulphur existing as monosulphide of potassium was calculated from the weight of the manganous oxide, and the difference between it and the sulphur found in the cupric oxide (in determination *e*) was taken to represent excess of sulphur, or *free sulphur*, and was added to the result of determination *d*, the necessary correction being made in the number furnished by determination *e*.

k. Total amount of potassium.—The solution of the residue, after treatment with cupric oxide, was evaporated with excess of sulphuric acid, and the residue repeatedly treated with ammonium carbonate and ignited, until the weight of potassium sulphate was constant. Or water and sulphuric acid were added to about 4 grms. of the residue, and after boiling to expel sulphurous acid, two or three drops of nitric acid were added to peroxidise the little iron in solution and excess of ammonia to precipitate the latter. The precipitate and insoluble matters (glass, etc.) were then filtered off, and the solution evaporated, the weight of potassium sulphate being ascertained by treatment of the residue as already described. In this way the amount of potassium arrived at indirectly, by the determinations of the several substances with which it existed in combination, was controlled by direct estimation.

l. Ammonium sesquicarbonate.—The solution of about 12 grms. of the residue was diluted to 1 litre; the liquid was then carefully distilled until about 250 c.c. remained in the retort, the distillate being allowed to pass into dilute chlorhydric acid. As some minute quantities of potassium salt might have passed over, the distillate was returned to a retort, mixed with excess of sodium carbonate and again distilled, the product passing into dilute chlorhydric acid. This second distillate was evaporated, and the ammonium determined as platinum salt with the usual precautions, the weight of the latter being controlled by ignition and determination of the weight of the platinum.

m. Potassium nitrate.—The portion of solution remaining in the retort, after the first distillation above described, was acidified with sulphuric acid; a piece of thin sheet zinc was then placed in the liquid and allowed to remain for a week, a small quantity of sulphuric acid being occasionally added. After the lapse of that time the zinc was removed, and the ammonia produced from any nitrate existing in the liquid was determined exactly as at *l.*

(*e*) COMPOSITION OF THE GUNPOWDERS EMPLOYED.

The method pursued in determining the proportions of proximate constituents in the samples of gunpowder present but very few points of difference from those ordinarily adopted, and need therefore not be detailed.

It may be mentioned, however, with reference to the determination of the proportion of saltpetre, that a very appreciable amount of the most finely-divided particles of the charcoal generally passes through the filter during the final washings, however carefully the operation be conducted.

These last washings, which contain only a very small proportion of the saltpetre, were therefore evaporated separately, and the residue was carefully heated until the small quantity of charcoal was completely oxidised. The resulting carbonate was then converted into nitrate by careful treatment with dilute nitric acid, and the product added to the remainder of the saltpetre previously extracted.

The composition of the charcoal contained in the powders was determined by combustion, after as complete a separation of the other constituents as possible. There was, of course, no difficulty in completely extracting the saltpetre; but the sulphur cannot be

entirely removed from the charcoal by digestion and repeated washings with pure carbon disulphide. The amount remaining was therefore always determined by oxidation of the charcoal, and estimation of sulphuric acid produced; the necessary correction thus arrived at was made in the amount of charcoal used for analysis. The latter was dried by exposing it for some time (in the platinum boat in which it was to be burned) to a temperature of about 170° in a current of pure dry hydrogen; it was allowed nearly to cool in this gas, and dry air was then passed over for some time, the boat being afterwards rapidly transferred to a well-stoppered tube for weighing. The dried charcoal was burned in a very slow current of pure dry oxygen, the resulting products being allowed to pass over the red-hot cupric oxide, and finally over a layer of about 8 inches of lead chromate, heated to incipient redness. The efficiency of this layer in retaining all sulphurous acid was fully established by preliminary test experiments.

The following tabular statement (Table 2, p. 128) gives the percentage composition of the five samples * of gunpowder employed in these investigations as deduced from the analytical results.

In every instance at least two determinations were made of each constituent, the means of closely concordant results being given in the table.

This table also includes the results of analysis by Bunsen and Schischkoff, Karolyi, Linck, and Federow, of the gunpowders employed in their experiments.

It will be seen that the several English service-powders of Waltham-Abbey manufacture did not differ from each other very importantly in composition; the most noteworthy points of difference are the somewhat low proportion of saltpetre in the F. G. powder and the slightly higher proportion of carbon in the pebble-powder.

The charcoals contained in these powders presented some decided differences in composition, as is shown by the following comparative statement:—

	Pebble.	R. L. G.	R. F. G.	F. G.
Carbon .	85·26	80·32	75·72	77·88
Hydrogen .	2·98	3·08	3·70	3·37
Oxygen .	10·16	14·75	18·84	17·60
Ash . .	1·60	1·85	1·74	1·15

* The authors are indebted to Colonel C. W. Younghusband, R.A., F.R.S., the Superintendent of the Waltham-Abbey Gunpowder Works, for having selected and furnished to them the samples of English gunpowder employed in their investigations.

TABLE 2.—*Results of Analysis of Gunpowders employed in these investigations, and of those used by other Investigators.*

Components per cent.	Description of Gunpowder employed in experiments.				
	Pebble-powder. Waltham-Abbey.	Rifle Large-grain. Waltham-Abbey.	Rifle Fine-grain. Waltham-Abbey.	Fine-grain. Waltham-Abbey.	Spanish Spherical Pebble-powder.
Saltpetre	74·67	74·95	75·04	73·55	75·30
Potassium sulphate	0·09	0·15	0·14	0·36	0·27
Potassium chloride	......	......	......	......	0·02
Sulphur	10·07	10·27	9·93	10·02	12·42
Charcoal	14·22	13·52	14·09	14·59	11·34
Carbon	12·12	10·86	10·67	11·36	8·65
Hydrogen	0·42	0·42	0·52	0·49	0·38
Oxygen	1·45	1·99	2·66	2·57	1·68
Ash	0·23	0·25	0·24	0·17	0·63
Water	0·95	1·11	0·80	1·48	0·65
	Gunpowders employed by other Investigators.				
	Bunsen and Schischkoff. Sporting-powder.	Karolyi. Austrian cannon-powder.	Karolyi. Austrian small-arm powder.	Linck. Würtemburg cannon-powder.	Federow.* Russian powder.
Saltpetre	77·99	73·78	77·15	74·66	74·18
Sulphur	9·84	12·80	8·63	12·49	9·89
Charcoal	11·17	13·39	14.27	12·85	14·83
Carbon	7·69	10·88	11·78	12·31	10·75
Hydrogen	0·41	0·38	0·42	0.54	0·43
Oxygen	3·07	1·82	1·79		3·31
Ash	traces	0·31	0·28		0·34
Water	......	......	......	......	1·10

* This is the only analysis of powder, by foreign investigators of the subject, in which the proportion of water, existing as a constituent of the powder experimented with, is given.

The charcoal in the P. powder is somewhat more highly burned than that in the R. L. G., and decidedly more than the F. G. charcoal; that contained in the R. F. G. powder is prepared from a different wood to the others, which is known to furnish a comparatively quick-burning charcoal. Although, however, the charcoals themselves differ very decidedly from each other, it will be seen that the percentages of carbon in the gunpowders do not present great differences, the widest being between the P. and R. F. G. powders.

The Spanish spherical pebble-powder was specially selected from various other foreign powders for purposes of experiment, on account of the comparatively wide difference presented in composition between it and the English powders, the proportion of sulphur being high, and that of carbon being low. The charcoal in this powder (made from hemp) had the following percentage composition:—

Carbon	76·29
Hydrogen	3·31
Oxygen	14·87
Ash	5·53

The proportions of carbon and hydrogen are therefore similar to those existing in the F. G. powder; but the amount of ash in the hemp-charcoal is very high compared to that contained in the charcoals from light woods used generally in the manufacture of gunpowder.

All the powders used by the recent foreign experimenters differed very decidedly both from each other and from the powders employed by us. The sporting-powder of Bunsen and Schischkoff, and Karolyi's small-arm powder, were of very exceptional composition, while the Russian powder used by Federow was the only one resembling our service-powders in composition.

(*f*) EXAMINATION OF THE ANALYTICAL RESULTS.

Table 3 gives the composition in volumes per cent. of the gases, and the percentage composition of the solid products furnished by a number of experiments with the different gunpowders, the charges exploded having occupied various spaces in the explosion-chambers. This table also includes the results obtained by other recent experimenters in the analytical examination of the products of explosion of gunpowder. (See p. 130.)

TABLE 3.—*Showing the analytical results obtained*

No. of experiment.	Description of experiment.	Percentage composition by volume of the gas.						
		Carbonic anhydride.	Carbonic oxide.	Nitrogen.	Sulphhydric acid.	Marsh-gas.	Hydrogen.	Oxygen.
8	Pebble-powder, Waltham-Abbey make, the space occupied by the charge in the chamber being......about 10 p.c.	46·66	14·76	32·75	3·13	...	2·70	...
7	,, ,, ,, 20 ,,	44·78	16·09	31·31	4·23	...	3·59	...
9	,, ,, ,, 30 ,,	47·03	15·51	31·71	2·90	...	2·84	...
12	,, ,, ,, 40 ,,	49·52	13·95	32·16	1·70	0·32	2·35	...
14	,, ,, ,, 50 ,,	49·82	13·36	32·19	1·96	0·58	2·08	...
37*	,, ,, ,, 60 ,,	49·48	13·75	31·83	2·24	0·55	2·15	...
38*	,, ,, ,, 70 ,,	49·93	12·51	32·08	3·18	0·35	1·95	...
43	,, ,, ,, 80 ,,	51·54	11·88	32·61	1·96	0·34	1·67	...
77*	,, ,, ,, 90 ,,	51·75	10·87	32·72	2·13	0·68	1·85	...
1	R.L.G. powder, Waltham-Abbey make, proportion of space occupied by the charge in the chamber...about 10 p.c.	48·99	8·98	35·60	4·06	0·29	2·07	...
3	,, ,, ,, 20 ,,	46·56	11·47	35·13	3·58	0·07	2·62	0·57
4	,, ,, ,, 30 ,,	49.34	11·60	32·96	3·11	...	2·98	...
11*	,, ,, ,, 40 ,,	52·05	10·89	34·23	1·93	0·28	2·47	...
‡70*	,, ,, ,, 50 ,,	47·21	17·04	30·29	1·61	0·84	3·01	...
39	,, ,, ,, 60 ,,	50·22	13·93	31·74	1·62	0·35	2·14	...
41*	,, ,, ,, 70 ,,	49·74	13·38	31·95	2·85	0·55	1·53	...
44	,, ,, ,, 80 ,,	51·62	12·16	32·16	1·56	0·77	1·72	...
68	,, ,, ,, 90 ,,	52·65	10·73	32·64	1·90	0·81	1·27	...
16	Fine-grain powder, Waltham-Abbey make, proportion of space occupied by the charge in the chamber about 10 p.c.	44·76	†	...	2·26	...	...	0·15
17	,, ,, ,, 20 ,,	47·41	12·35	32·35	3·76	...	4·13	...
18	,, ,, ,, 30 ,,	50·45	11·33	32·22	2·21	...	3·51	0·28
19*	,, ,, ,, 40 ,,	51·79	10·31	32·54	2·00	...	3·36	...
75	,, ,, ,, 50 ,,	51·04	10·38	33·15	2·20	0·27	2·96	...
40*	,, ,, ,, 60 ,,	52·00	9·60	33·28	2·26	0·18	2·68	...
42	,, ,, ,, 70 ,,	53·02	7·91	34·26	2·03	0·50	2·13	0·15
47	,, ,, ,, 80 ,,	51·80	8·32	34·64	2·61	0·41	2·04	0·18
69	,, ,, ,, 90 ,,	53·34	7·71	33·81	2·95	0·16	2·04	...
78	R.F.G. powder, Waltham-Abbey make, proportion of space occupied by the charge in the chamber...about 70 p.c.	52·4	8·86	34·51	1·60	0·12	2·51	...
79*	Spanish spherical powder........70 p.c.	53·34	4·62	37·80	2·74	...	1·29	0·21
	Experiments by Foreign Chemists.							
	Bunsen and Schischkoff, sporting-powder..................................	52·69	3·88	41·12	0·60	...	1·21	0·52
	Karolyi, Austrian cannon-powder......	42·74	10·19	37·58	0·86	2·70	5·93	...
	,, ,, small-arm powder..	48·90	5·18	35·33	0·67	3·02	6·90	...
	Linck, Würtemburg war-powder......	52·14	4·33	34·68	7·18	...	1·63	0·04
	Federow's Russian war-powder.........	...	...	...	...	...	...	...
	3 lb. fired in 9 R. gun, residue collected	...	...	...	...	...	...	...
	,, Residue collected by firing pistol with blank cartridge in a long glass tube..........................	...	...	...	...	...	...	...

* The analyses marked * added February 1875.

‡ In this experiment the powder was exploded by detonation.

Percentage composition by weight of the solid residue.										Proportion by weight of total gaseous products.	Proportion by weight of total solid products.
Potassium carbonate.	Potassium sulphate.	Potassium hyposulphite.	Potassium monosulphide.	Potassium sulphocyanate.	Potassium nitrate.	Potassium oxide.	Ammonium sesqui-carbonate.	Sulphur.	Charcoal.		
55·50	15·02	20·73	7·41	0·09	0·48	...	0·16	0·61	trace	43·88	56·12
57·47	13·72	3·71	18·07	0·06	...	...	0·09	6·88	...	44·05	55·96
59·43	12·61	4·32	16·51	0·21	0·03	...	0·17	6·72	trace	44·26	55·74
55·22	13·20	14·08	9·70	0·24	0·09	...	0·07	6·06	1·35§	43·02	56·98
56·15	11·93	6·12	19·12	0·23	0·20	...	0·08	6·17	trace	44·83	55·17
57·52	13·47	9·95	11·47	0·35	0·31	...	0·06	6·87	...	43·62	56·38
50·20	12·78	32·18	2·23	0·38	0·24	...	0·06	1·93	...	42·65	57·35
58·85	10·33	20·69	3·90	0·28	0·31	...	0·08	5·38	...	43·00	57·00
64·20	9·13	13·27	3·83	0·57	0·43	...	0·12	8·45	...	42·67	57·33
52·56	20·47	20·37	4·02	trace	0·56	...	0·06	1·25	0·71	42·78	57·22
54·66	24·09	5·75	9·56	0·05	0·12	...	0·06	5·69	0·02	42·77	57·23
52·40	24·22	12·85	5·86	0·05	0·03	...	0·04	4·55	trace	42·42	57·58
48·68	22·87	24·06	2·02	0·16	0·12	...	0·04	2·05	...	42·02	57·98
60·65	4·64	25·33	3·55	0·29	0·50	...	0·10	4·94	...	41·96	58·04
63·82	10·98	6·48	9·92	0·26	...	...	0·11	8·43	trace	43·05	56·95
60·27	10·52	18·60	3·84	0·49	0·43	...	0·08	5·77	...	42·44	57·56
66·51	8·81	3·08	9·05	0·25	0·17	...	0·10	12·03	trace	42·59	57·41
65·71	8·52	8·59	7·23	0·36	0·19	...	0·18	9·22	...	42·86	57·14
49·29	17·86	23·76	3·43	trace	0·20	5·39	0·07	traces	trace	...	...
59·39	24·22	5·30	5·12	0·02	0·08	...	0·15	5·72	trace	41·83	58·17
...	...	...	...	...	...	...	...	...	...	...	...
44·88	21·77	28·61	3·37	0·07	0·09	...	0·04	1·17	...	41·76	58·24
56·01	20·72	13·42	4·34	0·07	0·09	...	0·08	5·27	...	41·89	58·11
41·88	22·21	31·92	...	0·16	0·17	3·21	0·01	0·44	trace	42·00	58·00
43·03	21·00	32·07	...	0·23	0·19	2·98	0·03	0·47	trace	41·92	58·08
43·63	21·13	34·61	...	0·24	0·26	...	0·04	0·09	...	41·50	58·50
50·64	18·36	25·87	2·66	0·25	0·26	...	0·03	1·93	...	42·20	57·80
58·94	21·89	8·15	4·22	0·04	0·06	...	0·06	6·65	trace	41·52	58·48
34·97	47·62	7·60	3·17	0·04	0·93	...	0·04	5·63	...	37·81	62·19
						Potassium hydrate					
27·02	56·62	7·57	1·06	0·86	5·19	1·26	...	...	0·97	31·38	68·06
28·02	53·37	4·11	0·15	...	...	...	3·87	6·78	3·70	...	...
31·90	55·53	2·71	..	...	...	...	4·09	1·78	3·99	...	...
23·97	45·06	14·96	5·82	1·80	1·87	...	3·18	0·48	2·86	35·51	64·15
37·00	15·00	8·28	38·19	0·33	...	...	...	0·09	...	...	...
36·20	15·15	7·44	39·55	0·33	...	...	...	0·09	1·02	...	...
23·44	48·25	16·53	0·97	0·54	5·81	...	...	4·30	4·08	...	...

† About 16 p.c.; this analysis was interrupted accidentally.
§ Foreign matter, etc., not estimated.

No. of experiment.	Nature of powder.	Mean density of products of combustion.	Pressure of explosion in tons per sq. inch.	Proportion by weight of solid products.	Proportion by weight of total gaseous products.	Proportions by weight					
						K_2CO_3	$K_2S_2O_3$	K_2SO_4	K_2S.	KCNS.	KNO_3
8	Pebble	·10	1·3	·5612	·4388	·3115	·1163	·0843	·0416	·0005	·0027
1	R. L. G.	·10	1·6	·5722	·4278	·3007	·1166	·1171	·0230	·0000	·0032
16	F. G.	·10	1·7								
7	Pebble	·20	2·9	·5596	·4404	·3216	·0208	·0768	·1011	·0003	...
3	R. L. G.	·20	2·7	·5723	·4277	·3128	·0329	·1378	·0547	·0003	·0007
17	F. G.	·20	3·7	·5817	·4183	·3454	·0308	·1409	·0298	·0001	·0005
9	Pebble	·30	4·9	·5574	·4426	·3312	·0241	·0703	·0920	·0012	·0002
4	R. L. G.	·30	6·4	·5758	·4242	·3017	·0740	·1395	·0337	·0003	·0002
	F. G.	·30									
12	P.	·40	9·1	·5698	·4302	·3146	·0802	·0752	·0553	·0014	·0005
11*	R. L. G.	·40	8·1	·5790	·4210	·2819	·1393	·1324	·0117	·0009	·0007
19*	F. G.	·40	9·9	·5824	·4176	·2615	·1666	·1268	·0196	·0004	·0005
14	P.	·50	12·2	·5517	·4483	·3098	·0338	·0658	·1055	·0013	·0011
†70*	R. L. G.	·50	10·7	·5804	·4196	·3520	·1470	·0269	·0206	·0017	·0029
75*	F. G.	·50	10·2	·5811	·4180	·3255	·0780	·1204	·0252	·0004	·0005
37*	P.	·60	14·8	·5638	·4362	·3245	·0561	·0759	·0647	·0019	·0017
39	R. L. G.	·60	14·4	·5695	·4305	·3635	·0369	·0625	·0565	·0015	...
40*	F. G.	·60	14·1	·5800	·4200	·2429	·1851	·1288	...	·0009	·0010
79*	Spanish	·70	17·0	·6219	·3781	·2175	·0473	·2962	·0197	·0003	·0058
38*	P.	·70	18·6	·5735	·4265	·2879	·1845	·0733	·0128	·0022	·0014
41*	R. L. G.	·70	19·5	·5756	·4244	·3470	·1070	·0606	·0221	·0028	·0024
42	F. G.	·70	18·2	·5808	·4192	·2499	·1863	·1220	...	·0013	·0011
78*	R. F. G.	·70	18·9	·5848	·4152	·3447	·0477	·1279	·0247	·0002	·0004
43*	P.	·80	28·6	·5700	·4300	·3354	·1179	·0589	·0222	·0026	·0018
44	R. L. G.	·80	24·4	·5741	·4259	·3818	·0177	·0506	·0519	·0014	·0010
47*	F. G.	·80	27·1	·5850	·4150	·2553	·2025	·1236	...	·0014	·0015
77*	P.	·90	31·4	·5733	·4267	·3680	·0761	·0523	·0220	·0033	·0025
68	R. L. G.	·90	35·6	·5714	·4286	·3755	·0491	·0487	·0413	·0021	·0011
69*	F. G.	·90	27·2	·5780	·4220	·2927	·1495	·1061	·0154	·0014	·0015
						K_2CO_3	$K_2S_2O_3$	K_2SO_4	K_2S.	KCNS.	KNO_3

* The analyses marked * added February 1875.

of solid products.				Proportions by weight of gaseous products.							Volume of ga calculated from analysis.
$(NH_4)_2CO_3$	C.	Free S.	Not estimated.	SH_2	O.	CO.	CO_2	CH_4	H.	N.	
·0009	...	·0034	...	·0134	...	·0519	·2577	...	·0007	·1151	281
·0003	·0072	·0041	...	·0041	...	·0303	·2597	·0006	·0005	·1201	269
·0005	...	·0385	...	·0184	...	·0575	·2517	...	·0009	·1119	285
·0004	·0001	·0326	...	·0149	·0022	·0393	·2504	·0001	·0006	·1202	272
·0009	...	·0333	...	·0154	...	·0416	·2512	...	·0010	·1091	267
·0007	...	·0375	...	·0125	...	·0550	·2620	...	·0007	·1124	283
·0002	...	·0262	...	·0127	...	·0390	·2610	...	·0007	·1108	268
·0004	...	·0345	·0077	·0070	...	·0475	·2650	·0006	·0006	·1095	279
·0002	...	·0119	...	·0078	...	·0360	·2624	·0005	·0006	·1137	265
·0002	...	·0068	...	·0080	...	·0339	·2678	...	·0008	·1071	262
·0004	...	·0340	...	·0084	...	·0473	·2770	·0012	·0005	·1139	282
·0006	...	·0287	...	·0066	...	·0563	·2522	·0016	·0007	·1022	269
·0005	...	·0306	...	·0088	...	·0343	·2650	·0005	·0007	·1096	263
·0003	...	·0387	...	·0094	...	·0474	·2681	·0011	·0005	·1097	275
·0006	...	·0480	K_2O	·0067	...	·0472	·2677	·0007	·0005	·1077	270
·0186	trace	·0026	·0186	·0090	...	·0316	·2689	·0003	·0006	·1096	258
·0002	...	·0350	...	·0097	·0007	·0134	·2440	...	·0003	·1100	232
·0003	...	·0111	...	·0129	...	·0419	·2630	·0007	·0005	·1075	268
·0001	...	·0332	K_2O	·0115	...	·0446	·2604	·0011	·0004	·1064	267
·0002	...	·0027	·0173	·0081	·0006	·0258	·2718	·0009	·0005	·1117	260
·0005	...	·0389	...	·0063	...	·0287	·2673	·0002	·0006	·1120	259
·0005	...	·0307	...	·0080	...	·0399	·2717	·0006	·0004	·1094	269
·0006	...	·0691	...	·0063	...	·0405	·2702	·0014	·0004	·1071	268
·0002	...	·0005	...	·0102	·0007	·0270	·2637	·0008	·0005	·1121	259
·0007	...	·0484	...	·0086	...	·0362	·2710	·0013	·0005	·1090	266
·0009	...	·0527	...	·0077	...	·0356	·2750	·0015	·0003	·1085	268
·0002	...	·0112	...	·0017	...	·0252	·2738	·0003	·0005	·1105	254
$(NH_4)_2CO_3$	C.	S.	...	SH_2	O.	CO.	CO_2	CH_4	H.	N.	

† In this experiment the powder was exploded by detonation.

Table 4, pp. 132 and 133, shows the composition by weights of the products of combustion furnished by 1 grm. of gunpowder under the different circumstances of our experiments. The complicated nature of the analysis of these products has rendered it impossible to complete the examination of the entire series furnished by our experiments; we trust, however, at a future time to fill up the blanks * remaining in this tabular statement.

A comparison of the analytical data furnished by our examination of the products of explosion of gunpowder with those obtained by Bunsen and Schischkoff and other recent investigators of this subject, points to the following principal differences in the results arrived at:—

As regards the *gaseous* products: the proportion of carbonic oxide is considerably lower in Bunsen and Schischkoff's analysis and in one of Karolyi's than in the results obtained by us; this might, in the case of Bunsen and Schischkoff's results, be ascribed to the fact that the proportion which the saltpetre bears to the carbon in the English powder is lower than in the powder used by them, and that the proportion of sulphur is also lower. The Austrian cannon-powder employed by Karolyi, which is not widely different from the English cannon (R. L. G.) powder, as regards the proportion of saltpetre and carbon, though containing a higher proportion of sulphur, furnished amounts of carbonic anhydride and carbonic oxide more nearly approaching those obtained with the English powder at a low pressure. But the other (small-arms) powder used by him furnished almost as low an amount of carbonic oxide as obtained by Bunsen and Schischkoff, although the proportion of saltpetre to the carbon in this powder was about the same as in the other used by him. This result may be ascribable to the smaller proportion of sulphur existing in the former. The Würtemburg powder used by Linck, which was made apparently with a very highly burned charcoal, but contained a similar proportion of saltpetre to the English powder and a high proportion of sulphur, also furnished a comparatively very small quantity of carbonic oxide. The proportions of this gas and of carbonic anhydride which it yielded were very similar to those obtained by Bunsen and Schischkoff with a gunpowder of widely different composition, though the method of experiment pursued in the two instances was the same. Although the proportion of hydrogen contained in the powder with which Linck experimented was very low, the amount of sulphuretted hydrogen which it furnished was remark-

* The majority of these blanks have been now filled up.

ably high; and in this respect again the analysis differs greatly from that of the products similarly obtained by Bunsen and Schischkoff. The proportions of water existing in the gunpowders used by these several experimenters is not stated, but it must probably have been very considerable in Linck's powder.

The *solid* products of explosion obtained by Bunsen and Schischkoff, Linck, and Karolyi differ remarkably from those furnished by our experiments. The potassium sulphate obtained by them was in Linck's analysis about double, and in those of the other chemists more than double the highest amount we found.* The potassium carbonate furnished in the German experiments was about half that produced in ours; and the proportion of potassium sulphide found in the greater number of powder-residues which we examined was very greatly in excess of the results obtained by the German experimenters. Linck found a large proportion of potassium hyposulphite in the solid products obtained by him, while the other chemists found comparatively small amounts of this constituent; in our results (which will presently be compared among themselves) the hyposulphite was also found to vary in amount very greatly. These fluctuations were found by us, in most cases, to bear definite relation to those of the sulphide; but this is not observed to be the case in the analysis of Linck and Bunsen and Schischkoff on comparing them with ours.

The method pursued by these chemists for obtaining the products of decomposition of powder was of a nature calculated to furnish very variable results, which can scarcely be accepted as corresponding to those produced when gunpowder is exploded in an absolutely closed space or in the bore of a gun.

By allowing the powder-grains to drop gradually into a heated open bulb, not only is their decomposition accomplished under very different conditions to those attending the explosion of a confined charge of powder, but the solid products are necessarily subjected to further changes during their continued exposure to a high temperature and to the action of fresh quantities of powder deflagrated in contact with them. An imperfect metamorphosis of the powder-grains themselves and further secondary changes in the composition of the residue deposited (which will vary in extent with the duration of the experiment), the amount of heat applied externally, and the rate at which the powder-grains are successively deflagrated appear

* Excepting in the case of a Spanish powder, which differed widely in composition from the other experimented with by us.—February 1875.

to be inevitable results of this mode of operation. A comparison of Bunsen and Schischkoff's results with those shortly afterwards obtained by Linck in Bunsen's laboratory, the same method being pursued for effecting the decomposition of the powder, appears to demonstrate this conclusively.

The differences in the composition of the powders operated upon in the two investigations would certainly not suffice to account for the important differences exhibited by the results of analysis of the residues. The comparatively large proportion of potassium sulphide, the much larger proportion of hyposulphite, and the considerably smaller proportion of sulphate found by Linck, appear to indicate that the operation of burning the powder was conducted much more rapidly by him, a view which is supported by the fact that, while he found a considerable proportion of ammonium carbonate in the residue, none existed in the product obtained by Bunsen and Schischkoff, who, however, found this constituent in the so-called powder-smoke which they collected in a long tube through which the gas escaped.

Our experiments have demonstrated conclusively that, even when the conditions under which the explosion of powder is effected in distinct operations are as closely alike as possible, very exceptional results, as regards the composition of the solid residue, may be obtained, Experiments 7 and 17, 9 and 4, 14 and 70 being illustrations of this. Yet in no instance, however apparently abnormal, did any considerable proportion of potassium *nitrate* escape decomposition, the highest amounts discovered in the residues being 0·48 and 0·56 per cent. (Experiments 1 and 8). These percentages existed in the products of explosion of powder formed under the *lowest* pressure; in only two instances, at higher pressures, were similar proportions found. The existence of so large a proportion as 5 per cent. of potassium nitrate in the residue obtained by Bunsen and Schischkoff, the coexistence of 7·5 per cent. of hyposulphite and small quantities of other oxidisable substances, and the existence also of a comparatively high proportion of oxygen in the gaseous products, appear to indicate the occurrence of reactions in the course of the preparation of gas and residue, by the gradual deflagration of the powder, which were distinct from those attending the ordinary explosion of powder in a confined space.

The very considerable differences between the results of our analyses and of the experiments of Bunsen and Schischkoff and of Linck appear therefore clearly ascribable to the fact that the defla-

gration of gunpowder, as carried out by them, cannot be expected to furnish results similar to those produced when a charge of powder is exploded in a confined space under considerable pressure and in one operation.

This conclusion receives support from the results of analysis of powder-residues published by Federow. Those products, which he collected from a cannon in which 3 lbs. of powder were fired, furnished analytical results much more nearly resembling those obtained by us than those of Bunsen and Schischkoff; the proportion of sulphate was similar to that obtained in many of our experiments, and therefore very much below that of the German experimenters, while the proportion of sulphide was very considerably higher than the largest amount obtained by us—a result, we believe, not difficult of explanation. In the residue collected in a glass tube by firing small quantities of powder (blank charges) in a pistol, which therefore were not exploded under any considerable pressure, and were consequently subjected to more gradual change, the results were of very different nature, the proportion of sulphate being comparatively very high, and that of the sulphide very low.

That the mode of operation pursued by Karolyi should have furnished results similar to those obtained by Bunsen and Schischkoff's method is at first sight somewhat surprising, inasmuch as, by the arrangement which he adopted, the powder-charge was exploded in an envelope (a small thin shell) offering some amount of initial resistance. But as this explosion was accomplished in a capacious *exhausted* chamber, the pressure developed upon the first ignition of the charge suffered a sudden reduction at the moment that the shell was fractured, and most probably, therefore, before the entire charge had exploded. Hence it might have been expected that some portions of the oxidisable constituents of powder would escape oxidation, either entirely or partly, and that, at any rate, the oxidation of the sulphur would not be effected to the complete extent observed in operating according to Bunsen and Schischkoff's plan. But it appears that in one instance not a trace, and in another only 0·15 per cent., of potassium sulphide was found in the solid products, the proportion of hyposulphite found being at the same time much smaller than that observed by Bunsen and Schischkoff; so that the sulphur-compounds obtained consisted chiefly of the highest product of oxidation, and yet in each of the two experiments nearly 4 per cent. of charcoal and a large proportion of hydrogen escaped oxidation altogether. In one experiment nearly

7 per cent. of sulphur appears to have been left in an uncombined state.

In our experiments, in which the powder was exploded under more or less considerable and sustained pressure, the complete oxidation of the sulphur might certainly be expected to have been favoured to a much greater extent than in Karolyi's experiments; yet in all but one experiment, made with a powder of exceptional composition, the proportion of sulphate formed was very greatly below that found by Karolyi. The irreconcilable nature of Karolyi's analytical results, though probably in some measure ascribable to the exceptional conditions under which he obtained his products, does not appear satisfactorily accounted for thereby.

On examination and comparison with each other of the analytical results given in the foregoing tables, the following points suggest themselves:—

Excluding the results of a few explosions of marked exceptional character as regards the *solid* products furnished, and those produced under the lowest pressure, which were naturally expected to yield variable and discordant results, there is considerable similarity, not only between the products furnished by pebble-powder when exploded under different conditions as regards pressure, but also between the results obtained with this powder and with the sample of R. L. G. powder employed in the experiments, which did not differ greatly in composition from it. The proportion of carbon was slightly lower in the R. L. G. than in the pebble-powder; and this fact is in harmony with the proportion by weight which the total gaseous constituents bear to the solid in the products obtained with the two powders, it being somewhat the highest, in most instances, in the case of the pebble-powder. The proportion of carbonic oxide is often rather higher in the gas obtained from the pebble-powder than in that furnished by the R. L. G. powder; and this is in accordance with the fact that the proportion of carbon is somewhat higher, while that of the saltpetre is a little lower, in the former than in the latter. Excluding the results furnished by the experiments in which the powder was exploded in the largest space (in which, therefore, the gases were developed at the lowest pressures), it will be observed that with the slowest-burning powder (the pebble) the proportion of carbonic oxide decreases steadily, while that of the anhydride increases, in proportion to the pressure developed at the time of explosion.

The proportion of carbonic anhydride is about the same in the gas from the two gunpowders specified; but that of the potassium carbonate is somewhat different, and appears regulated by circumstances other than the composition of the powder, being highest in the residues furnished by the R. L. G. powder at the higher pressures, and lowest in those of the same powder furnished at lower pressures. The amount of carbonate furnished by the pebble-powder under different conditions as to pressure varies, on the other hand, comparatively little, except at the highest pressure.*

The occasional occurrence of a small quantity of marsh-gas, like that of oxygen, is evidently an accidental result, being observed in some instances in the products obtained at low pressures, and the reverse in other instances.

In the gaseous products from the F. G. powder formed at pressures up to 50 per cent. space, the carbonic oxide existed in proportions similar to those furnished by the R. L. G. powder. If the relative proportions of potassium nitrate and carbon in the powders furnished an indication of the proportions in which this gas should be formed, this particular powder should have furnished a higher proportion of carbonic oxide than the R. L. G., as it contains 0·5 per cent. more carbon and 1·4 per cent. less saltpetre than the latter; but then the proportion of sulphur in it is lower by 0·25 per cent.; moreover, the charcoal in the F. G. was less highly burned, and therefore more rapidly oxidisable, a circumstance which may have a decided influence upon the amount of carbonic oxide produced by the explosion of gunpowder, distinct from that exerted by the proportion in which the ingredients exist. The difference in the amounts of carbonic oxide produced from this powder at the lower and the higher pressures is more marked than in the case of the other powders, the quantity in this as in the pebble-powder decreasing decidedly as the pressure increases. The amount of carbonic anhydride which it furnished at the highest pressure (the powder occupied 90 per cent. of the space) is the largest found in any of the gaseous products;† but that produced when the powder occupied 70 per cent. of the total space was very nearly as high, while the amount obtained in the intermediate experiment (80 per cent. space) was decidedly

* In 90 per cent. space the amount of carbonate formed was nearly equal to the proportions found in the residues from R. L. G. produced at the higher pressures.

† Except in the case of the Spanish powder, which furnished an equally high proportion.

lower, and corresponded closely to the proportions produced at the same pressure from R. L. G. and pebble-powder.

In the experiments with P. and R. L. G. (excluding the explosions in 10 per cent. space) the amount of sulphuretted hydrogen was highest at the lowest pressures; in the case of R. L. G. powder the proportion fell gradually with the increase of pressure, excepting at the highest pressure; with pebble a similar relation was indicated, though much less regularly; with F. G. it was still less apparent, and with all three powders the proportion of this gas rose somewhat again at the highest pressure. With pebble and F. G. the hydrogen exhibited a steady diminution with increase of pressure, and a similar though less regular result was observable with R. L. G. It need be scarcely stated that the proportions of sulphuretted hydrogen and of hydrogen are in no instance sufficiently high to enter into account in a consideration of what are the chief reactions which occur upon the explosion of powder.*

While the results, as regards *gaseous* products, furnished by the three gunpowders above referred to were on the whole remarkably uniform, the composition of the *solid* residues exhibited comparatively great variations. Certain general results appear, however, to be well established by a number of the analyses. Excluding, again, those experiments conducted at the lowest pressure, the proportion of potassium sulphate produced in the several experiments, with the comparatively slow-burning pebble-powder, was remarkably uniform at various pressures, being, as already pointed out, not more than one-fourth the amount found in powder-residue by Bunsen and Schischkoff. The proportion of sulphur not actually entering into the principal reactions involved in the explosion of the powder was also, with two exceptions, very uniform, being about 35 per cent. of the total amount contained in the powder. The proportion of potassium carbonate obtained from pebble-powder was somewhat less

* The additional analyses which we have made since this paper was presented to the Royal Society enable us to summarise the general results furnished by examination of the gaseous products as follows :—(*a*) With all the powders the proportion of carbonic anhydride produced increases steadily and decidedly with the pressure; (*b*) with the P. and F. G. powders the carbonic oxide decreases steadily as the pressure increases; and the same is generally true as regards the R. L. G. powder, although the series of analyses exhibits some violent fluctuations; (*c*) the proportions of sulphuretted hydrogen and of hydrogen furnished by all the powders fall somewhat as the pressures increase, though the diminution is not very decided or regular; (*d*) free oxygen was in no case found in the products from P. powder; in one instance it was found in those from R. L. G., and it occurred in four instances in those from F. G.

uniform, but did not differ greatly in the different experiments with the same powder exploded in different spaces, excepting at the highest pressure. With the more rapidly-exploding R. L. G. powder, the sulphate formed at the lower pressures was nearly double that obtained with pebble-powder; while at the highest pressures the amounts furnished by the two powders did not differ greatly, the amount of sulphur excluded from the chief reaction at those pressures, with R. L. G., being, however, more considerable than was the case with pebble-powder under similar conditions. With regard to this part of the sulphur contained in the powder, which corresponds to what Bunsen and Schischkoff term *free* sulphur, some portion of it almost always exists, not in combination with potassium as poly-sulphide, but combined with iron, and is therefore discovered in the residue left undissolved, upon treatment with water, of the solid products removed from the chamber. This proportion of the sulphur is evidently at once fixed, at the instant of explosion, by union with parts of the metal surfaces presented by the interior of the vessel in which the operation is conducted. The extent to which sulphur is thus abstracted from the powder-constituents, and precluded from entering into the reactions which are established by the explosion, or follow immediately upon it, must depend in some degree upon accidental circumstances, such as variations in the mechanical condition (smoothness, brightness, etc.) of the metal surfaces, and also upon the temperature developed at the instant of the explosion. The circumstance that, in the statement of the results of Experiment 42, both potassium oxide and sulphur are separately included is therefore explained by the above fact. The larger proportion of the "sulphur" specified in the several analyses existed as potassium polysulphide, and may therefore be styled *free* sulphur, as it did not take part in the chief reactions.

The *carbonate,* like the sulphate, differed decidedly in amount in the residues furnished by the R. L. G. powder exploded in the smaller and the larger spaces; in the former it was equal to the lowest result furnished by the pebble-powder; in the others its proportion was about 10 per cent. higher than in the pebble-residues, excepting in one of them produced at the highest pressure. In the products obtained by the explosion of the smallest-grain powder (F. G.) the variations in the proportions of carbonate are somewhat considerable; the proportions of sulphate were, on the other hand, much alike, except at the highest and lowest pressures. The proportion of hypo-sulphite was generally high, and that of the sulphide low, as com-

pared with the proportions of these constituents in the other powder-residues just discussed. In two of the residues from F. G., the proportion of sulphur which did not enter into the principal reactions is about the same as that found in the pebble-powder residues; while in three others only small quantities of free sulphur existed—in two of these there was free potassium oxide. Two of the residues (Nos. 42 and 47) contained not a trace of potassium sulphide discoverable by the most delicate test (sodium nitroprusside).

With respect to the proportions of potassium sulphide and potassium hyposulphite found in the several residues analysed, the following points appear to be worthy of note:—

1. In the residues obtained by exploding pebble, R. L. G., and F. G. under the lowest pressures (the charges only occupying 10 per cent. of the total space), the proportion of potassium hyposulphite is in all cases high, while that of the sulphide is correspondingly low.

2. In the comparatively slow-burning pebble-powder, the products of explosion of which at different pressures exhibited great similarity in many respects, there is a marked fluctuation in the proportion of hyposulphite; and this corresponds to a fluctuation, in the opposite direction, in the amount of sulphide found, while the sulphate varies but little. A similar fluctuation and relation is observed, as regards these two constituents, in the solid products of the experiments made with R. L. G. powder at the *lowest* pressures, but not, or only to a slight extent, in the residues furnished by the powder at higher pressures.

3. In most of the residues from F. G., the hyposulphite is large in amount and the sulphide small: in two of these (Nos. 42 and 47), which did not contain a trace of potassium sulphide, the proportion of hyposulphite was considerably higher than in any of the other experiments; * and in these cases there was no free sulphur—that is to say, no sulphur in the form of *polysulphide*, the small proportion given under the head of "sulphur" in the tabulated results being found in combination with iron derived from the interior of the chamber.

The circumstance that the hyposulphite generally existed in large proportions when the sulphide was small in amount, appeared at first sight to afford grounds for the belief that its production might be ascribable to a secondary reaction resulting in the oxidation of sulphide by carbonic anhydride, a view which might appear

* One residue furnished by P. powder (Experiment 38) contained a similarly high amount and a very small quantity of sulphide.

to receive support from the following circumstance. The upper portion of the solidified mass in the cylinder was found to contain a considerably larger proportion of hyposulphite than the remainder, as is demonstrated by the following results of a separate examination of the top and the lower portions of the residues, obtained by exploding a charge of 6804 grains (440·9 grms.) of R. L. G. powder, which occupied 90 per cent. of total space in the chamber (Experiment 68):—

Residue.	Carbonate.	Sulphate.	Hyposulphite.	Sulphide.	Sulphur.
Top portion .	52·15	7·69	17·14	6·03	4·88
Lower portion .	67·75	7·44	4·34	7·30	10·09

Similar results were obtained by the separate examination of the top part of other residues. Again, one of the small drops or buttons of the fused solid products which have been mentioned as being generally found upon the firing-plug in the cylinder (the residue of this particular experiment contained a somewhat considerable proportion of sulphide) was found to be quite free from sulphide, but contained hyposulphite. Lastly, a mixture of potassium carbonate and sulphide, after exposure in a crucible for 30 minutes to a temperature of about 1700° Cent. in a Siemens furnace (in which the atmosphere consisted of carbonic anhydride, carbonic oxide, and nitrogen), was found to contain a small quantity of hyposulphite. The production of this substance, as the result of a secondary reaction, should, however, be rendered evident by a marked increase in the proportion of carbonic oxide in all instances in which a large amount of hyposulphite was found: and this was certainly not the case, as will be seen by a comparison of the results of Experiments 8 and 7, 3 and 11, 19 and 17.

Experiment.	Carbonic anhydride.	Carbonic oxide.	Potassium carbonate.	Potassium sulphate.	Potassium hyposulphite.	Potassium sulphide.
8. Pebble .	·2577	·0519	·3115	·0843	·1163	·0416
7. Pebble .	·2517	·0575	·3216	·0768	·0208	·1011
3. R. L. G. .	·2504	·0393	·3128	·1378	·0329	·0547
11. R. L. G. .	·2624	·0360	·2819	·1324	·1393	·0117
19. F. G. .	·2678	·0339	·2615	·1268	·1666	·0196
17. F. G. .	·2512	·0416	·3454	·1409	·0308	·0298

It appears, therefore, that the formation of hyposulphite cannot be regarded as due to the occurrence of a secondary reaction between carbonic anhydride or carbonate and sulphide produced upon the explosion of gunpowder, but that it must be formed either during the

primary reaction of the powder-constituents on each other (in other words, by the direct oxidising action of saltpetre), or by an oxidation of sulphide by liberated oxygen following immediately upon the first change (which results in the formation of a large quantity of sulphide), and being regulated in extent by the amount of oxygen liberated at the moment of explosion. The view that hyposulphite must be, at any rate in part, due to the oxidation of sulphide formed in the first instance, appears to be supported by the circumstance that the proportion of the latter in the powder-residues is as variable as that of the hyposulphite, and is generally low when the hyposulphite is high. Moreover, in our experiments the proportion of *sulphate* is, except possibly in a few instances, apparently not affected by the amount of hyposulphite formed. On the other hand, the amount of sulphur which exists either in combination with iron (and other metals derived from the exploding-apparatus) or as polysulphide of potassium, and which therefore has not entered into the chief reactions, is generally low where the hyposulphite is high, which appears to indicate that the latter is also formed (at any rate occasionally) by an oxidation of free sulphur following immediately upon the first reaction.

In the products of decomposition of the powder examined by Bunsen and Schischkoff, which were obtained, at any rate to a considerable extent, by a continued process of oxidation, the conversion of sulphur into the highest product (sulphate) was effected to a very great extent, there being no free sulphur and only an exceedingly small quantity of sulphide; but when the deflagration and action of heat were arrested, there was still a considerable proportion (7·5 per cent.) of *hyposulphite* existing in the solid residue. The *smoke*, or portions of the solid products mechanically carried away by the gases evolved and afterwards deposited, was found by those chemists also to contain as much as 4·9 per cent. of hyposulphite, while neither sulphide nor free sulphur were discovered (the sulphate being, on the other hand, considerably higher in amount than in the residue itself); the gas which escaped contained a very appreciable amount of free oxygen, and there was 5 per cent. of nitrate left in the residue when the operation was arrested. Here, therefore, the view appears a very probable one that the hyposulphite constituted an intermediate product of a reaction following upon the production of sulphide in the first instance. In Linck's experiment, conducted in the same way, the process of deflagration being, however, apparently arrested at an earlier stage, more than twice the

amount of hyposulphite found by Bunsen and Schischkoff existed in the residue, while there were still nearly 6 per cent. of sulphide and 0·5 per cent. of sulphur unoxidised, and a considerably smaller amount of sulphate formed. This difference between the results of two experiments conducted on the same plan may certainly be partly ascribed to the difference in the composition of the two gunpowders experimented with, as that used by Linck was nearly of normal composition, and contained nearly 3 per cent. more sulphur, and quite 3 per cent. less saltpetre, than Bunsen and Schischkoff's powder; yet this very circumstance appears to support the view that, at the first instant of explosion, sulphide is formed in considerable proportion, its immediate oxidation and the nature and extent of that oxidation being regulated by the proportion of oxygen which is liberated at the time that the sulphide is formed, the same also applying to the proportion of sulphur which at the moment of explosion does not combine with potassium to form sulphide.

Potassium hyposulphite is stated to decompose at about 200° Cent.; but it is evidently formed at very much higher temperatures; and the experiments of Bunsen and Schischkoff and of Linck demonstrated that it may remain undecomposed, or may continue to be produced, in powder-residue which is maintained at a high temperature.

We ourselves have exposed portions of powder-residue obtained in our experiments for lengthened periods to the heat of a Siemens furnace (1700° Cent.), and have still detected small quantities of hyposulphite in the material after such exposure.

It will be seen on comparing our analytical results with the pressures recorded in the several experiments as being developed by the explosions, that the latter are not affected by very great differences in the composition of the products, or by important variations in the extent to which particular reactions appear to predominate over others. The pressures developed by explosion of the pebble and R. L. G. powders, under corresponding conditions as regards the relation of charge to total space, were almost identical up to the highest density; and the same was the case with F. G. powder at the lower densities; yet there were in several instances very considerable differences between the products formed from the different powders under the same pressures (or accompanied by the development of corresponding pressures), differences which were certainly not to be accounted for by the respective constitution of those powders.

The composition of the gases and residues obtained in Experiments 3, 7, and 17, and 12, 11, and 19 (Tables 3 and 4) may be referred to in illustration of this. (See pp. 130 and 132.)

A cursory inspection of the analytical results at once shows that the variations in composition of the *solid* products furnished by the different powders, and even by the same powder under different conditions, are much more considerable than in those of the gaseous products; and it is evident that the reactions which occur among the powder-constituents, in addition to those which result in the development of gas, of fairly uniform composition (and very uniform as regards the proportions which it bears to the solid), from powders not differing widely in constitution from each other, are susceptible of very considerable variations, regarding the causes of which it appears only possible to form conjectures. Any attempt to express, even in a comparatively complicated chemical equation, the nature of the metamorphosis which a gunpowder of average composition may be considered to undergo, when exploded in a confined space, would therefore only be calculated to convey an erroneous impression as to the simplicity, or the definite nature, of the chemical results and their uniformity under different conditions, while it would, in reality, possess no important bearing upon an elucidation of the theory of explosion of gunpowder.

The extensive experiments which the Committee on Explosive Substances has instituted, with English and foreign gunpowders of very various composition, have conclusively demonstrated that the influence exerted upon the action of fired gunpowder by comparatively very considerable variations in the *constitution* of the gunpowder (except in the case of *small* charges applied in firearms) is often very small as compared with (or even more than counterbalanced by) the modifying effects of variations in the mechanical * and physical properties of the powder (*i.e.*, in its density, hardness, the size and form of the grains or individual masses, etc.). Hence it is not surprising to find that a fine-grained gunpowder, which

* The desirability of applying these means to effecting modifications in the action of fired gunpowder was pointed out by Colonel Boxer in a memorandum submitted to the War Office in 1859; and the first Government Committee on Gunpowder, soon afterwards appointed (of which Colonel Boxer and Mr Abel were members), obtained successful results, which were reported officially in 1864, by limiting the alterations in the manufacture of gunpowder intended for use in heavy guns to modifications in the form, size, density, and hardness of the individual grains or masses, the composition of the powder remaining unaltered. The Committee on Explosive Substances have adhered to this system in producing gunpowder suitable for the largest ordnance of the present day.

differs much more in mechanical than in chemical points from the larger powder (R. L. G.) used in these experiments, should present decided differences, not only in regard to the pressures which it develops under similar conditions, but also as regards the proportions and uniformity of the products which its explosion furnishes. On the other hand, the differences in regard to size of individual masses and other mechanical peculiarities between the R. L. G. and pebble powders are, comparatively, not so considerable, and are in directions much less likely to affect the results obtained by explosions in perfectly closed spaces.

Again, the analysis of solid residues furnished by different kinds of gunpowder which presented marked differences in composition, did not establish points of difference which could be traced to any influence exerted by such variations; indeed, the proportions of the several products composing residues which were furnished by one and the same powder, in distinct experiments made at different pressures, differed in several instances quite as greatly as those found in some of the residues of different powders which presented decided differences in composition. This will be seen on comparing with each other the analysis of certain residues of P. powder (*e.g.* Experiments 7 and 12), of R. L. G. powder (*e.g.* Experiments 4 and 39), and of F. G. powder (Experiments 17 and 42), and on then comparing the composition of the residues of F. G. and R. F. G. obtained in Experiments 17 and 18.

When, however, the deviation from the normal composition of cannon-powder is comparatively great, a decided influence is thereby exerted upon the proportions in which the products of explosion are formed. Thus, in the Spanish pebble-powder specially selected by us for experiment on account of the considerable difference between its composition and that of the English powders, the proportion which the saltpetre bears to the carbon is comparatively high, while the amount of sulphur it contains is very high. An examination of the gaseous products which it furnished shows that the proportion of carbonic oxide is only one-half the amount produced under precisely the same conditions, as regards pressure, by R. F. G. powder, and about one-third the amount contained in the products furnished by pebble and R. L. G. powders under nearly similar conditions. With respect to the solid products of explosion obtained with the Spanish powder, they also present several points of great difference from the products furnished by the powders of English manufacture. The amount of potassium carbonate is very much lower than in any of

the other residues examined, and the sulphate very much exceeds in amount the largest proportion furnished by the English powders. The proportion of sulphide is small, while that of hyposulphite is also not considerable.

Although, for the reasons given in the foregoing, we cannot attempt to offer anything approaching a precise expression of the chemical changes which gunpowder of average composition undergoes when exploded in a confined space, we feel warranted by the results of our experiments, in stating, with confidence, that the chemical theory of the decomposition of gunpowder, as based upon the results of Bunsen and Schischkoff, and accepted in recent text-books, is certainly as far from correctly representing the general metamorphosis of gunpowder as was the old and long-accepted theory, according to which the primary products were simply potassium sulphide, carbonic anhydride, and nitrogen.

Moreover, the following broad facts regarding the products furnished by the explosion of gunpowder appear to us to have been established by the analytical results given in this paper:—

1. The proportion of carbonic oxide produced in the explosion of a gunpowder in which the saltpetre and charcoal exist in proportions calculated, according to the old theory, to produce carbonic anhydride only, is much more considerable than hitherto accepted.

2. The amount of the potassium carbonate formed, under all conditions (as regards nature of the gunpowder and pressure under which it is exploded), is very much larger than has hitherto been considered to be produced, according to the results of Bunsen and Schischkoff and more recent experimenters.

3. The potassium sulphate furnished by a powder of average normal composition is very much smaller in amount than found by Bunsen and Schischkoff, Linck, and Karolyi.

4. Potassium sulphide is never present in very considerable amount, though generally in much larger proportion than found by Bunsen and Schischkoff; and there appears to be strong reason for believing that in most instances it exists in large amount as a primary result of the explosion of gunpowder.

5. Potassium hyposulphite is an important product of the decomposition of gunpowder in closed spaces, though very variable in amount. It appears probable (as above pointed out) that its production is in some measure subservient to that of the sulphide; and it may perhaps be regarded as representing, at any rate to a considerable extent, that substance in powder-residue—*i.e.*, as having

resulted, partially and to a variable extent, from the oxidation, by liberated oxygen, of sulphide, which has been formed in the first instance.

6. The proportion of sulphur which does not enter into the primary reaction on the explosion of powder is very variable, being in some instances high, while, in apparently exceptional results, the whole amount of sulphur contained in the powder becomes involved in the metamorphosis. In the case of pebble-powder, the mechanical condition (size and regularity of grain) of which is perhaps more favourable to uniformity of decomposition under varied conditions as regards pressure than that of the smaller powders, the amount of sulphur which remains as potassium polysulphide is very uniform, except in the products obtained at the lowest pressure; and it is noteworthy that with R. L. G. powder, under the same conditions, comparatively little sulphur escapes; while in the case of F. G. powder, under corresponding circumstances, there is no free sulphur at all.

7. But little can be said with regard to those products, gaseous and solid, which, though almost always occurring in small quantities in the products, and though apparently, in some instances, obeying certain rules with respect to the proportion in which they are formed, as already pointed out, cannot be regarded as important results of the explosion of powder. It may, however, be remarked that the regular formation of such substances as potassium sulphocyanate and ammonium carbonate, the regular escape of hydrogen and sulphhydric acid from oxidation, while oxygen is occasionally coexistent, and the frequent occurrence of appreciable proportions of potassium nitrate, indicate a complexity as well as an incompleteness in the metamorphosis. Such complexity and incompleteness are, on the one hand, a natural result of the great abruptness as well as the comparative difficulty with which the reactions between the ingredients of the mechanical mixture take place; on the other hand, they favour the view that, even during the exceedingly brief period within which chemical activity continues, other changes may occur (in addition to the most simple, which follow immediately upon the ignition of the powder) when explosions take place at pressures such as are developed under practical conditions.

The tendency to incompleteness of metamorphosis, and also to the development of secondary reactions under favourable conditions, appears to be fairly demonstrated by the results obtained in exploding the different powders in spaces ten times that which the charges

occupied (Experiments 8, 1, and 16). It appears, however, that, even under apparently the most favourable conditions to uniformity of metamorphosis (namely, in explosions produced under high pressures), accidental circumstances may operate detrimentally to the simplicity and completeness of the reactions. But the fact, indisputably demonstrated in the course of these researches, that such accidental variations in the nature of the changes resulting from the explosion do not, even when very considerable, affect the force exerted by fired gunpowder, as demonstrated by the recorded pressures, etc., indicate that a minute examination into the nature of the products of explosion of powder does not necessarily contribute directly to a comprehension of the causes which may operate in modifying the action of fired gunpowder.

(*g*) VOLUME OF THE PERMANENT GASES.

The results of the experiments made to determine the quantity of permanent gases generated by the explosion of the three service-powders which we have employed, are given in Nos. 53 to 62 and 64.

From a discussion of these results it appears that, in the case of pebble-powder, the combustion of 386·2 grms. gave rise respectively to 106,357·8, 105,716·2, and 107,335·8 c.c. of gas at a temperature of 0° Cent. and a barometric pressure of 760 mm.; or, stating the result per grm. of powder, the combustion of 1 grm. pebble generated respectively 275·4, 273·7, and 277·9 c.c., or a mean of 275·68 c.c., at the above temperature and pressure.

From the combustion of a similar quantity of R. L. G. powder resulted 106,080·4, 103,676·5, and 104,606·7 c.c., or 274·7, 268·45, and 270·86 c.c. of gas (mean = 271·34 c.c.) per grm. of powder; while 99,694·9, 101,372·3, 99,164·8, and 100,289·0, or 262·4, 258·1, 256·8, and 259·68 (mean 259·2) c.c. per grm. were yielded by the F. G. powder.

The difference in quantity of gas between the pebble and the R. L. G. is very slight; but there appears to be a decided difference in the quantity generated by F. G. powder, the defect being much greater than can be accounted for by any errors of observation.

The results of those experiments show that the quantity of permanent gases generated by 1 grm. of the service pebble or R. L. G.

powders is about 276 c.c. at 0° Cent. and 760 mm.—that is, they occupy at this temperature and pressure about 276 times the volume of the unexploded powder.

The volume given off by F. G. is less, being about 260 volumes; and, if we may trust to the single measurement we have made of the permanent gases of R. F. G. (in Experiment 80), the volume generated by this powder does not differ greatly from that given off by F. G.

With the view of ascertaining whether a powder of a marked difference in composition, such as the Spanish spherical pellet powder, gave the same quantity of permanent gases as our service-powders, a measurement of the volume generated by this powder was made (in Experiment 81).

The quantity was found to be notably less, being only 232·7 volumes; but this measurement was the result of one determination only.

(*h*) RESULTS OF EXPLOSION, DEDUCED BY CALCULATION FROM ANALYTICAL DATA.

We are now in a position to apply two important tests to the results at which we have arrived as regards composition of products and measurement of gases. From a consideration of the analysis of the solid products of explosion, we are able to deduce the total weight of the solid residue, and thence, by difference, the weight of the gaseous products. On the other hand, from a consideration of the measurement of the volume of the gaseous products, combined with their analysis, we can calculate the weight of the gaseous and, by difference, that of the solid products; and if these calculations accord, a valuable corroboration of the accuracy of our results will be obtained. We can also compare the amounts of the elementary substances in the powder before and after combustion, and so obtain a still further corroboration of accuracy.

We have applied these tests to all the analyses completed; and we proceed to give two illustrations of the method—one applied to pebble, the other to F. G. powder.

In Experiment 12, 411·085 grms. pebble-powder were fired, and the products of combustion collected and analysed. The analysis of this powder has been already given; but for our present purpose it is convenient to give the proportions of the components, as found by analysis, in their elementary form.

The pebble-powder, then, consisted of :—

	Percentage composition.	Composition by weight. grms.
K	·2886	118·639
C	·1212	49·824
S	·1007	41·396
H	·0052	2·138
O	·3742	153·828
N	·1078	44·315
Ash	·0023	·945
	1·0000	411·085

while the composition of the solid products of combustion was found to be :—

K_2CO_3	·55220	KCNS	·00244
$K_2S_2O_3$	·14080	KNO_3	·00084
K_2SO_4	·13200	$(NH_4)_2CO_3$	·00067
K_2S	·09700	S	·06058
		Not estimated	·01347

Now almost any practical method of weighing the solid residue would give us inexact results, the weight of the vessel used for explosion being too great to allow of sufficient accuracy if weighed in the vessel, and the hygroscopic nature of the residue, as well as the difficulty of removing it, preventing its being weighed after removal. But we can arrive at the weight in the following manner:—We know that the whole of the potassium originally contained in the powder will be found in the solid residue; we further know that potassium enters into the composition of potassium carbonate, hyposulphite, sulphate, sulphide, and sulphocyanate in the proportions respectively of 565, 411, 448, 709, and 402 parts out of every thousand. Hence if x be the weight of the solid residue, we have the following equation :—

$$\{\cdot565 \times \cdot55220 + \cdot411 \times \cdot14080 + \cdot448 \times \cdot13200 + \cdot709 \times \cdot09700 + \cdot402 \times \cdot00244 + \cdot386 \times \cdot00084\}\, x = 118\cdot639,$$

118·639 grms. being the amount of potassium originally in the powder.

Hence x = solid products = 237·717 grms. = ·5783, and, by difference, gaseous products = 173·368 grms. = ·4217.

We can now perform the inverse process, and, from the measurement of the gas and the gaseous analysis, arrive at the weight of the

solid products. Since 1 grm. of pebble-powder gave rise to 275·68 c.c. of permanent gases, 411·085 grms. will generate 113,797·9 c.c. But the analysis of the permanent gases, in this particular experiment, gave SH_2 ·0170 volume, CO ·1395, CO_2 ·4952, CH_4 ·0032, H ·0235, N ·3216 volumes, while a c.c. of these gases weighs respectively ·001523, ·001254, ·001971, ·0000896, and ·001254 grm. Hence we have as follows:—

	vols.		c.c.	grms.	weight.
SH_2 .	·0170	=	1,934·6	2·946	·0163
CO .	·1395	=	15,874·8	19·907	·1104
CO_2 .	·4952	=	56,352·7	111·071	·6160
CH_4 .	·0032	=	364·2	·261	·0015
H . .	·0235	=	2,674·3	·240	·0013
N . .	·3216	=	36,597·4	45·893	·2545
	1·0000		113,798·0	180·318	1·0000

Hence, taking the gas-measurement and analysis combined as the basis of calculation, we have:—

Gaseous products = 180·318 grms.
Solid products = 230·767 grms.

or, if we take the mean of the two determinations as more nearly representing the truth—

Solid products = 234·242 grms. = ·5698
Gaseous products = 176·843 grms. = ·4302

Resolving the solid products of combustion into their elements, we have the following scheme:—

	Grms.	K.	C.	S.	H.	O.	N.
K_2CO_3 . .	129·348	73·082	11·253	...	...	45·013	...
$K_2S_2O_3$ . .	32·981	13·555	...	11·115	...	8·311	...
K_2SO_4 . .	30·920	13·852	...	5·689	...	11·379	...
K_2S . . .	22·721	16·109	...	6·612	...	...	...
KCNS . .	·572	·230	·069	·083	...	...	·189
KNO_3 . .	·197	·077	...	·095	...	...	·027
$(NH_4)_2CO_3$.	·157	·078	·020	...	·013	...	·046
C	...	...	...	...	...	...	...
S	14·190	...	...	14·190	...	...	...
Not estimated .	3·155	...	...	1·263	...	...	...
Totals . .	234·241	116·983	11·342	39·047	·013	64·703	·262

Following the same plan with the gaseous products and comparing the total weights of the elements found with those existing in the powder before combustion, we have:—

	Grms.	K.	C.	S.	H.	O.	N.
SH_2	2·882	...	...	2·712	0·170	...	...
O	...	...	...	...	...	...	...
CO	19·523	...	8·375	...	...	11·148	...
CO_2	108·936	...	29·740	...	...	79·196	...
CH_4	·265	...	·199	...	·066	...	...
H	·230	...	...	...	·230	...	...
N	45·007	...	...	...	...	...	45·007
Total gaseous .	176·843	...	38·314	2·712	·466	90·344	45·007
Total solid .	234·241	116·983	11·342	39·047	·013	64·703	·262
Total found .	411·084	116·983	49·656	41·759	·479	155·047	45·269
Total originally in powder .	411·085	118·639	49·824	41·396	2·138	153·828	45·000
Errors . .	...	− 1·656	− 0·168	+ ·363	− 1·659	+ 1·219	+ ·269

If we perform similar calculations in the case of Experiment 17, when 205·542 grms. of F. G. were exploded, and the products found to be of the undermentioned composition:—

Solid Products.				Gaseous Products.	vol.
K_2CO_3 .	·5939	$(NH_4)_2CO_3$.	·0015	SH_2 .	·0376
$K_2S_2O_3$.	·0530	S . . .	·0572	CO .	·1235
K_2SO_4 .	·2422			CO_2 .	·4741
K_2S . .	·0512			CH_4 .	...
KCNS .	·0002			H .	·0413
KNO_3 .	·0008			N .	·3235

we obtain:—

For solid products . .	119·554 grms.	=	·5817
For gaseous products .	85·987 grms.	=	·4183

or, resolving these products as before into their elements:—

	Grms.	K.	C.	S.	H.	O.	N.
K_2CO_3 . .	71·003	40·117	6·177	...	...	24·709	...
$K_2S_2O_3$ . .	6·336	2·604	...	2·135	...	1·597	...
K_2SO_4 . .	28·956	12·972	...	5·328	...	10·656	...
K_2S . . .	6·121	4·340	...	1·781	...	...	...
KCNS . .	·024	·010	·003	·008	...	...	·003
KNO_3 . .	·096	·037	...	...	...	·045	·013
$(NH_4)_2CO_3$.	·179	...	·022	...	·015	·090	·052
C	...	...	...	...	...	...	...
S	6·839	...	...	6·839	...	...	...
Total solid .	119·554	60·080	6·202	16·091	·015	37·097	0·068
SH_2 . . .	3·164	...	...	2·977	·187	...	...
CO . . .	8·556	...	3·671	...	...	4·885	...
CO_2 . . .	51·644	...	14·099	...	...	37·545	...
CH_4 . . .	...	...	...	...	...	...	...
H . . .	·206	...	...	...	·206	...	...
N . . .	22·417	...	...	...	...	...	22·417
Gaseous . .	85·987	...	17·770	2·977	·393	42·430	22·417
Solid . . .	119·554	60·080	6·202	16·091	·015	37·097	0·068
	205·541	60·080	23·972	19·068	·408	79·527	22·485
Found originally in powder .	205·542	58·662	23·349	20·760	1·336	79·031	22·700
Errors . .	...	+1·418	+0·623	−1·692	−·928	+·496	−·215

It will be seen from this comparison that the results, when the nature of the analysis is taken into consideration, accord with great exactness. The volume of the gaseous products, calculated from the weight of the gases given in the first column of the table, would be about 279 c.c. at 0° Cent. and 760 mm. per grm. of powder in the case of the pebble, and 267 c.c. in the case of the F. G. powder. These volumes are slightly more than the measured volumes; but it must be remembered that it is not difficult to conceive causes which might tend to make the mean measured quantity of gas somewhat less than reality, while it is hardly possible that the reverse can be the case.

For example, without doubt an appreciable quantity of gas is occluded, as indicated by the conditions of the residues (see account of Experiments Nos. 10 and 38) and by the disengagement of gas generally observed upon addition of water to the residue. In some instances also there may be, under the high pressure of explosion, a trifling leakage from the apparatus.

One point we must not pass over without observation. The deficiency of hydrogen in the products of explosion, although absolutely small, is relatively very large. The question then arises as to whether the missing hydrogen may not be present in the form of aqueous vapour. None was detected in the analysis of the gases; but it is not difficult to explain this fact, as the extremely hygroscopic property of the residue would most effectually dry the gases—the absorption of the vapour by the residue being actually demonstrated by the greasiness observed on the surface of the deposit and on the sides of cylinder immediately on its being opened after explosion. The entire proportion of water formed or pre-existing must therefore have existed in the solid residues, but its determination therein was obviously impracticable.

The amount of water present can, however, be calculated from the deficiency of hydrogen shown in our tables.

(*i*) CONDITION OF PRODUCTS AT THE INSTANT OF, OR SHORTLY AFTER, EXPLOSION.

A careful examination of the contents of the cylinders after they were opened showed that, at all events shortly after explosion, the solid products were in a fluid state. It was of course impossible to open the cylinder while the solid products were still fluid; but it occurred to us that we might yet obtain valuable information as to the state of the contents at different periods after the explosion. Accordingly, in Experiment 40, the cylinder being about two-thirds filled with F. G., 30 seconds after the explosion the vessel was tilted so as to make an angle of 45°. Two minutes later it was restored to its first position.

On subsequent examination, the deposit was found to be lying at the angle of 45°, and the edges of the deposit were perfectly sharp and well defined.

In Experiment 41, the cylinder, being about three-fourths filled with R. L. G., was allowed to rest for 1 minute after explosion. It was then placed sharply at an angle of 45°, and 45 seconds later it was returned to its first position.

Upon opening, it was found that when the cylinder was tilted over, the deposit had just commenced to congeal; for upon the surface there had been a thin crust, which the more fluid deposit underneath had broken through. The deposit was lying at an angle

of 45°, but the crust through which the fluid had run was left standing like a thin sheet of ice.

Hence in this experiment, 1 minute after explosion, the non-gaseous products had commenced to congeal, and 45 seconds later they were solid.

In Experiment 77, the cylinder, being completely full of pebble-powder and fired, was placed at an angle of 45° 1 minute after explosion, and the position of the cylinder was altered every 15 seconds. It was found that at 60 and 75 seconds after explosion the deposit was perfectly fluid, the evidence of each motion of the cylinder being given by a wave of deposit. At 90 seconds, it was rather viscid; at 105 seconds, the deposit hardly moved.

Hence in this experiment it was rather more than a minute and three-quarters before the non-gaseous products became solid; and the conclusion from the experiments is that, very shortly after explosion, the non-gaseous products are collected as a fluid at the bottom of the exploding-vessel, and that some time elapses before these products finally assume the solid form.

(*j*) THE POSSIBILITY OF DISSOCIATION AMONG GASEOUS PRODUCTS CONSIDERED.

In the attempt to reconcile or account for the discordant estimate of the pressure exerted by fired gunpowder, some authorities have supposed that the phenomena connected with dissociation play an important part, and that, for example, the dissociation of carbonic anhydride into carbonic oxide and oxygen may give rise to a considerable increment of pressure.

Berthelot has enunciated the view that the tendency to dissociation at very high temperatures possessed by compound gases operates in preventing the formation, at the time of explosion, of certain of the constituents which exist in the ultimate gaseous products, and that during the expansion in the bore of the gun and the concomitant fall of temperature, the compound gases existing in those ultimate products are gradually formed. He,* indeed, points out that the effects of dissociation must not be exaggerated, and that the decomposing influence of high temperature in the case of an explosion may be altogether or in part compensated by the inverse influence of

* Berthelot, *Force de la Poudre, etc.*, 1872, p. 81.

pressure. Having given this subject our careful consideration, we cannot even go so far as Berthelot does in accepting the view that the results of explosion of powder in a gun are at all affected by dissociation, the occurrence of which we cannot consider probable, even when the pressure to which the gases are subjected in the bore of a gun is relieved to the maximum extent.

It is perhaps, however, worth while examining what would be the effect on the pressure if the particular case of dissociation to which we have alluded above actually occurred.

Among the products of combustion of 1 grm. of powder is ·28 grm. of CO_2, occupying, at 0° Cent. and 760 mm. pressure, 142 c.c.; now if we suppose this CO_2 dissociated into CO and O, the 142 c.c. of CO_2 would become 213 c.c. of the mixed gases, and the total quantity of gas generated by a grm. of powder (282 c.c.) would become 353 c.c.

On the other hand, the ·28 grm. of CO_2 contains ·0764 grm. Cent., which, burnt to CO_2, gives rise to 611 grm.-units, or burnt to CO, gives rise to 187 grm.-units.

Now if a molecule of carbonic oxide, in combining with another atom of oxygen and burning to carbonic anhydride, generates 424 units of heat, it is obvious that the reverse process, or dissociation of the carbonic anhydride into carbonic oxide and oxygen, must absorb precisely the same amount of heat.

Hence the dissociation we have supposed would absorb 424 grm.-units of heat, and the consequent loss of temperature would reduce the pressure in a degree that would far more than compensate for the increment due to the increase of volume by dissociation.

(*k*) TENSION OF FIRED GUNPOWDER OBSERVED IN A CLOSE VESSEL.

As it was one of our principal objects to determine with as much accuracy as possible, not only the tension of fired gunpowder when filling completely the space in which it was exploded, but also to determine the law according to which the tension varied with the density, it has been our endeavour to render both varied and complete the experiments instituted to ascertain these important points.

In the first experiments described in this paper, as well as in the earlier series which formed the basis of Captain Noble's lecture delivered to the Royal Institution, the method adopted to determine

the variation of pressure was as follows:—The space in which the powder was to be fired having been carefully established, the weight of the powder to be experimented with which would accurately fill the space was ascertained, and $\frac{1}{10}$, $\frac{2}{10}$, $\frac{3}{10}$, etc., of the vessel was successively filled with powder, which was then fired, and the resulting pressures determined.

Later on it was found that, as with each description of powder the gravimetric density varied, it was more convenient to refer the pressure not, as at first, to a density arrived at by taking the weight of powder which completely filled a given space as unity, but to the specific gravity of water as unity. The densities given hereafter must therefore be taken to represent the mean density of the powder inclusive of the interstitial spaces between the grains, or, what is the same thing, the mean density of the products of explosion referred to water as unity. The gravimetric density of the modern pebble powder closely approximates to 1;* that of the old class of cannon-powders, such as L. G., R. L. G., etc., varied generally between † ·870 and ·920; that of F. G. and sporting-powders was still lower.

The results of the whole of our experiments, as far as they relate to tension, arranged according to the three descriptions of the powder used and to the density of the products of explosion, are given in Table 5. The experiments numbered with an asterisk are taken from the earlier series made by Captain Noble. They accord very well with the present experiments; but the powder used in the first series not having been analysed, we are not prepared to say that it was of exactly the same constitution as the corresponding kind of powder used in the present experiments, although the difference could of course be but very trifling, it being gunpowder of Waltham-Abbey manufacture, which, as shown by the analyses given in Table 2, varies very little in composition.

* This statement applies only to the powder taken in considerable bulk. In our explosion-vessels, the gravimetric density, when they were completely filled, did not exceed, with pebble-powder, ·92 or ·93. The statement, therefore, that the powder was fired in so many per cent. of space does not actually refer to the space occupied in the chamber, but to a chamber of a size that would hold powder of our standard density.

† Boxer, Gen., R.A., *Treatise on Artillery*, 1859, p. 21. Mordecai, Major, U.S.A., *Report on Gunpowder*, Washington, 1845, p. 187.

[Table 5

TABLE 5.—*Giving the pressures actually observed, in tons per square inch, with F. G., R. L. G., and Pebble powders for various densities of the products of explosion.*

Mean density of products of explosion.	Nature of Powder. F. G. Pressure in tons per sq. inch.	Nature of Powder. R. L. G. Pressure in tons per sq. inch.	Nature of Powder. Pebble. Pressure in tons per sq. inch.	Mean density of products of explosion.	Nature of Powder. F. G. Pressure in tons per sq. inch.	Nature of Powder. R. L. G. Pressure in tons per sq. inch.	Nature of Powder. Pebble. Pressure in tons per sq. inch.
·0940	...	1·6	...	·5000	10·48	10·48	...
·1064	1·66	...	1·39	·5000	10·20	10·70	...
·1064	1·35	...	1·26	·5000	...	11·10	...
·1064	0·96	...	1·28	*·5300	...	*11·80	...
·1973	...	2·67	...	·5322	11·48	...	12·20
·2000	...	...	2·70	·6000	14·14	14·36	13·78
·2114	...	...	2·93	·6000	...	...	13·50
·2129	3·70	...	...	·6000	...	...	14·80
·2129	3·58	...	...	*·6100	...	*15·6	...
·2129	3·00	...	...	*·6200	...	*16·8	...
·2963	...	6·40	...	·7000	18·2	19·54	18·60
·3000	...	...	5·40	·7000	†18·9	...	‡17·00
·3171	...	...	4·90	*·7500	...	*21·90	...
·3193	6·75	...	...	·8000	23·20	24·40	28·60
·3193	6·32	...	...	·8000	27·10	23·20	24·20
*·3800	...	*8·5	...	·9000	27·20	35·6	33·40
...	...	*7·7	...	·9000	...	...	31·60
·3860	7·68	...	...	·9000	...	...	31·40
·3947	...	8·1	...	*·9000	...	*33·1	...
·4258	9·34	...	8·40	...	...	*30·7	...
·4258	...	...	9·10	...	...	*31·9	...
·4615	8·68	...	...	·9150	...	34·5	...
·4893	10·14	...	...	·9300	...	36·2	...
·4934	...	11·50	...	·9300	...	*34·0	§35·0

† R. F. G. powder. ‡ Spanish spherical pellet. § Pellet.

We have laid down on Plate XII., p. 230, the whole of these experiments. The pressures given by the pebble and the R. L. G. are nearly identical; we have therefore considered them so, and have drawn but one curve to represent their mean results. The curve representing the pressures given by the F. G., although nearly identical with the pebble and R. L. G. at the lower densities, does not coincide at the higher densities. A separate curve has therefore been drawn for this powder. The lower tension is perhaps accounted for by the difference between the quantity of permanent gas yielded by it and by the other two powders.

The corrected values of the tension, in terms of the density of the different powders, as indicated by the curves, Plate XII., p. 230, are given in the following table:—

TABLE 6.—*Showing the pressure corresponding to a given density of the products of explosion of F. G., R. L. G., and Pebble powders, as deduced from actual observation, in a close vessel. The pressures are given in tons per square inch, atmospheres, and kilogrammes per square centimetre.*

Mean density of products of explosion.	Corresponding pressures for Pebble and R. L. G. powders.			Corresponding pressures for F. G. powder.		
	In tons per sq. inch.	In atmospheres.	In kilos. per sq. centimetre.	In tons per sq. inch.	In atmospheres.	In kilos. per sq. centimetre.
·05	0·70	107	110·2	0·70	107	110·2
·10	1·47	224	231·5	1·47	224	231·5
·15	2·33	355	367·0	2·33	355	367·0
·20	3·26	496	513·4	3·26	497	513·4
·25	4·26	649	670·9	4·26	650	670·9
·30	5·33	812	839·4	5·33	812	839·4
·35	6·49	988	1028·1	6·49	988	1022·1
·40	7·75	1180	1220·5	7·74	1179	1219·0
·45	9·14	1392	1439·5	9·10	1387	1433·2
·50	10·69	1628	1683·6	10·59	1614	1667·8
·55	12·43	1893	1957·6	12·22	1863	1924·5
·60	14·39	2191	2266·3	14·02	2136	2208·0
·65	16·60	2528	2614·3	16·04	2445	2526·1
·70	19·09	2907	3006·5	18·31	2790	2883·6
·75	21·89	3333	3447·5	20·86	3179	3285·2
·80	25·03	3812	3942·0	23·71	3613	3734·1
·85	28·54	4346	4495·0	26·88	4096	4233·3
·90	32·46	4943	5112·1	30·39	4632	4786·1
·95	36·83	5608	5800·4	34·26	5190	5335·6
1·00	41·70	6350	6567·3	38·52	5870	6066·5

In considering the pressures indicated, the question naturally arises as to how their value would be affected if the charges were greatly increased; or, to put the question in another form, it may be inquired whether the tensions indicated by our experiments are materially affected by the cooling influence of the vessel in which the explosion is conducted.

We think there are very strong grounds for assuming that the pressure is not materially affected by the above circumstances, except in cases where the density of the products of explosion is low, and the quantity of powder therefore very small as compared with the space in which it is fired.

Thus it will be observed that the pressures obtained in Experiment 2 and in Experiments 65, 66, and 68 compare very well (the density being about the same), although the quantity of powder fired in the first case is only half of that fired in the last three experiments.

Again, if there were any considerable decrement of pressure due to loss of heat, we should expect to find that the tension indicated would be higher when means are taken to ensure rapidity of combustion. Such, however, is not the case; for if reference be made to Experiments 70 and 71, in which the charges were fired by means of mercuric fulminate, it will be observed that the tension realised in these experiments was not materially higher than when the powder was fired in the ordinary way.

We may cite also, in support of our view, some interesting observations made during some earlier experiments, in which charges of 10,500 grains (680·4 grms.) R. L. G. and pellet powder were fired in chambers entirely closed with the exception of a vent ·2 inch (5·08 mm.) in diameter.

With the former powder the pressure realised under these circumstances was 36·2 tons per square inch (5513 atmospheres), with the latter 17·3 tons (2634 atmospheres). This large difference was due to the slower combustion of the pellet-powder, upon the ignition of which, therefore, a large part of the products of combustion escaped by the vent before the whole of the powder was fired. When, however, the same powders were fired in vessels absolutely closed, the pressure indicated by the pellet-powder was more than doubled (being 35 tons per square inch, or 5330 atmospheres), while the pressure indicated by the R. L. G. was practically the same (being 34 tons per square inch, or 5178 atmospheres).

From the experiments made by the Committee on Explosives, we are able to name approximately the absolute time that would be consumed in burning a charge of R. L. G. and of pebble, assuming that the powder be confined. With R. L. G. the time would be approximately ·00128 second, with pebble approximately ·0052 second. Of course these figures must vary greatly with different powders, as they depend not only on the nature, size of grain, and density of the powder, but also on the mode of ignition. They are interesting, however, as indicating the minuteness of the times involved, and the relatively much larger time required for the decomposition of the pebble-powder. It follows, from the accordance of the pressures in the experiments just referred to, when powders differing so considerably in rapidity of combustion are fired in close vessels, that there is no very appreciable difference in pressure due to the longer time taken by the pebble-powder to consume under these conditions.

But the strongest, and at the same time an altogether independent, corroboration of our view is derived from the experiments upon the pressures exerted in the bores of guns by the action of the charge.

Not only do these pressures, as obtained by observation, agree with most remarkable accuracy with the theoretical pressures deduced from the experiments in a close vessel, but, when in large guns the tensions due to different charges are compared (not with reference to the position of the shot in the bore, but with reference to the mean density of the products of explosion), a most striking accordance is found to exist. We may therefore conclude that, where powders such as those we have experimented with are employed, there is but a trifling correction to be made in the observed pressure when the powder entirely fills the space in which it is fired, or, indeed, whenever it occupies a considerable percentage of that space. But though the pressure may not be seriously affected when the generated gases are of a high density, it is more than probable that some very appreciable correction should be made in the results we have observed when experimenting with gases of low density. In this latter case the cooling influence of the vessel would be greatly increased, not only from the higher ratio which the cooling surface bears to the charge, but also from the slowness of combustion due to the comparatively feeble pressure; and we think the effect of slow combustion is clearly traceable in the low tensions observed with pebble-powder (See curve, Plate XII., p. 230) at densities of ·1, ·2, and ·3, as compared with those given at corresponding densities by F. G. powder, the combustion of which would be much more rapid. But we shall return to this point when we compare our results with those demanded by theory.

Upon the same plate (Plate IX., p. 230), on which we have given curves representing the experiments of Rumford and Rodman, there is also laid down a curve representing our own experiments. The very high results obtained by Rumford are probably in great measure attributable to his methed of experiment. The charges being placed at one end of his little vessel, while the weight to be lifted, so to speak, closed the muzzle, the products of combustion acquired a high *vis viva* before striking the weight, and thus indicated a much higher pressure than that due to the tension of the gas, just as in Robins's well-known experiment a musket-barrel may be easily bulged or burst by a bullet placed at some distance from the charge. That Rumford's and even Piobert's corrected estimate of the tension of

fired gunpowder was very excessive, is of course indisputably proved by our experiments, as the vessels in which they were made were quite incapable of resisting pressures at all approaching those assigned by these eminent authorities.

Rodman's results are also too high, from a defect in the application of his system of measurement, which has elsewhere* been pointed out; and his experiments on the ratio of tension to density were not carried sufficiently far to admit of comparison in the more important portion of the curve.

(*l*) DETERMINATION OF HEAT GENERATED BY THE COMBUSTION OF GUNPOWDER.

The amount (that is the number of units) of heat liberated by the combustion of gunpowder is determined from Experiments Nos. 46, 47, 48, 49, and 63. (See pp. 221, etc.).

The powder used was the R. L. G. and F. G.; but as it was found that there was no material difference in the heat liberated, we have drawn no special distinction between the experiments made with the two brands.

In each of the Experiments Nos. 46, 48, and 63, 3800 grains (246·286 grms.) were exploded; and when the necessary reductions were made to convert the alterations in temperature which were observed into their equivalents in water, it was found that in Experiment 48 the explosion of 246·286 grms. F. G. was sufficient to raise 173,077·4 grms. of water through 1° Cent. In Experiment 48, the explosion of the same quantity of R. L. G. was equivalent to raising 172,569 grms. of water through 1° Cent., and in Experiment 63 to raising 171,500 grms. through 1° Cent.; or, expressing these results in a different form, it appears that the combustion of a grm. of powder gave rise to quantities of heat represented by raising a grm. of water through 702°·80 Cent., 700°·69 Cent., and 696°·50 Cent. respectively.

In Experiments 47 and 49, the charge used was 393·978 grms.; and it was found that in Experiment 47 the heat generated by the explosion of the F. G. was sufficient to raise 277,994·1 grms. of water through 1° Cent.; and in Experiment 49 the explosion of the same quantity of R. L. G. generated heat represented by the raising of 278,185·5 grms. through 1° Cent.,—or, in the two experiments,

* Noble, *loc. cit.* p. 25; *Revue Scientifique*, No. 48, p. 1138.

1 grm. of powder gave rise respectively to 705·61 and 706·09 grm.-units.

The mean of the whole of these experiments gives 702·34 grm.-units of heat generated by the explosion of a grm. of powder, and we shall probably have a very close approximation to the truth in assuming it at 705 grm.-units.

From this datum the temperature of explosion may be deduced, if we know the mean specific heat of the products of combustion. We have only to divide 705 by the specific heat, and the result is the required temperature.

The specific heat of all the gaseous products of combustion are known; and they have also been determined for the principal solid products at low temperatures, when they are (of course) in the solid form.

Bunsen and Schischkoff, from their experiments, deduced the temperature of explosion on the assumption that the specific heats of the solid products remain invariable over the great range of temperature through which they pass.

With every deference to those distinguished chemists we think their assumption is quite untenable. Without, we believe, any known exception, the specific heat is largely increased in passing from the solid to the liquid state. In the case of water, the specific heat is doubled; the specific heats of bromine, phosphorus, sulphur, and lead are increased from 25 to 40 per cent., and those of the nitrates of potassium and sodium nearly 50 per cent., while it is more than probable that, even with liquids, the specific heat increases very considerably with the temperature.

We shall, however, deduce from our experiments the temperature of explosion on Bunsen and Schischkoff's hypothesis, both with the view of enabling our results to be compared with theirs, and for the purpose of fixing a high limit to which it is certain the temperature of explosion cannot reach. We shall afterwards endeavour to estimate more accurately the true temperature.

The data necessary for computing the specific heat of a grm. of exploded powder are given in the subjoined table.

[TABLE 7.

TABLE 7.—*Showing the specific heats and proportions of the products generated by the combustion of gunpowder.*

1. Products of combustion.	2. Proportion in a gramme.	3. Specific heat.	4. Authority.	5. Products of columns 2 and 3.
Solid ·5684.				
Potassium carbonate .	·3382	·206	Kopp	·06967
" hyposulphite .	·0355	·197	Pape	·00700
" sulphate . .	·0882	·196	Kopp	·01729
" sulphide . .	·0630	·108	Bunsen	·00680
" sulphocyanate .	·0009	...	...	...
" nitrate . .	·0006	·239	Kopp	·00014
Ammonia carbonate . .	·0006	...	...	...
Sulphur	·0414	·171	Bunsen	·00708
Carbon	·0000	·242	Regnault	...
Gaseous ·4316.		At constant volume.		
Sulphuretted hydrogen .	·0113	·184	Clausius	·00208
Oxygen	·0000	·155	"	...
Carbonic oxide . . .	·0447	·174	"	·00778
Carbonic anhydride . .	·2628	·172	"	·04520
Marsh-gas	·0005	·468	"	·00024
Hydrogen	·0010	2·411	"	·00241
Nitrogen	·1113	·173	"	·01925
				·18494

Adding up the numbers in column 5, we obtain ·18494 as the mean specific heat of the products of explosion of a grm. of powder at ordinary temperatures; and since, as we have said, the temperature of explosion is obtained by dividing the grm.-units of heat by the specific heat, we have the temperature of explosion $=\frac{705}{\cdot 18494}=3812°$ Cent.; and we may accept this figure as indicating a temperature which is certainly not attained by the explosion of gunpowder. We defer until further on the consideration of the actual temperature.

(*m*) DETERMINATION OF VOLUME OF SOLID PRODUCTS AT ORDINARY TEMPERATURES.

The space occupied by the solid products of combustion at temperatures but little removed from 0°, is deduced from experiments Nos. 46, 48, 49, 57, 58, 60, 61, and 62. From these experiments it appears that

246·29	grms.	R. L. G.	gave rise to	76·46	c.c.	solid residue.
246·29	"	F. G.	"	67·26	"	"
393·98	"	R. L. G.	"	123·12	"	"

386·21	grms.	F. G.	gave rise to	115·34	c.c. solid residue.
386·21	„	R. L. G.	„	110·81	„ „
386·21	„	P.	„	111·78	„ „
386·21	„	R. L. G.	„	105·30	„ „
386·21	„	F. G.	„	108·54	„ „

Or, stating the results per grm. of powder, it appears that in the several experiments the solid products arising from the combustion of a grm. of powder occupied respectively ·3105, ·2731, ·3125, ·2987, ·2869, ·2894, ·2726, and ·2810 c.c.

The mean of these figures is ·2906; and we may thence conclude that at 0° Cent. the solid residue of 1 grm. of burned powder occupies a volume closely approximating to ·29 c.c.; therefore, since the solid products represent 57 per cent. of the original weight of the powder, it follows that at 0° Cent. the specific gravity of the residue is about 1·4.

(n) PRESSURE IN CLOSE VESSELS, DEDUCED FROM THEORETICAL CONSIDERATIONS.

From the investigations we have described, it appears that in a close vessel, at the moment of explosion, or at all events shortly afterwards, the results of the decomposition of a given charge (say 1 grm.) of powder such as we have experimented with, are as follows:—

1. About 43 per cent. by weight of permanent gases, occupying at 0° Cent. and under a pressure of 760 mm., a volume of about 280 c.c.

2. About 57 per cent. by weight of liquid product, occupying, when in the solid form and at 0° Cent., a volume of about ·3 c.c.

Now, if we assume that the conditions known to exist shortly after explosion obtain also at the moment of explosion, we are able, with the aid of our experiments, to compute the pressure, temperature of explosion, and volume occupied by the permanent gases. We propose to make these calculations, and then, by comparison with the results obtained under the varied conditions adopted in our experiments, to form an estimate of the correctness of our assumption. And, first, to establish a relation between the tension and the mean density of the products of explosion at the moment of ignition,—

Let ABCD (Plate XI., Fig. 4, p. 230) represent the interior of the vessel, of volume v, in which the experiments were made. Let CDEF represent the volume of a given charge of powder placed in the vessel. Let δ be the ratio which the volume CDEF bears to ABCD,

and let CDHG ($va\delta$ suppose) be the volume occupied by the liquid products at the moment and temperature of explosion.

It is obviously, for our present purpose, a matter of indifference whether we suppose the liquid products collected, as in the figure, at the bottom of the vessel or mixed with the permanent gases in a finely divided state.

Our conditions on explosion, then, are:—We have the space CDHG $= va\delta$ occupied by the fluid residue, and the space ABHG $= v(1 - a\delta)$ by the permanent gases.

Hence, since the tension of the permanent gases will vary directly as their density, we have, if p represent the pressure and D the density,

$$p = \mathrm{RD}_3 \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where R is a constant.

Now suppose the charge exploded in the chamber to be increased. In this case, not only is the density of the permanent gases increased on account of a larger quantity being generated, but the density is still further added to, from the gases being confined in a smaller space; the liquid residue CDHG being increased in a like proportion with the charge (D, in fact, varying as $\frac{\delta}{1 - a\delta}$), we have

$$p = \mathrm{R} . \frac{\delta}{1 - a\delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

or if p_0, δ_0, be corresponding known values of p and δ,

$$p = \frac{p_0(1 - a\delta_0)}{\delta_0} \, \frac{\delta}{1 - a\delta} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

In taking the tension of the permanent gases to vary directly as their density, we have of course assumed that the temperature, whatever be the value of δ, is the same.

In our experiments, the charges exploded have varied in quantity from that necessary to fill entirely the chamber to a small fraction of that quantity; but whatever the charge, it is obvious that if the vessel be considered impervious to heat (and we have already pointed out that only with the lower charges is there a material error due to this hypothesis), the temperature at the moment of explosion would be the same; for, as in the case of Joule's celebrated experiment, any heat converted into work by the expansion of the gases would again be restored to the form of heat by the impact of the particles against the sides of the vessel.

Returning to (3), the value of the constant a in this equation has

yet to be found. If, from Table 6, we take out a second pair of corresponding values p_1, δ_1, α is determined, and will be found $= \cdot 65$, very nearly. Taking $\alpha = \cdot 65$, and from Table 6, or the curve, Plate XII. (p. 230), taking $\delta_0 = \cdot 6$, $p_0 = 14 \cdot 4$ tons, Equation (3) becomes

$$p = 14 \cdot 63 \frac{\delta}{1 - \alpha\delta} \quad . \quad . \quad . \quad . \quad (4)$$

Substituting in this equation successively values of δ ·05, ·1, ·15, etc., we obtain computed values of p, which we compare with those derived directly from observation in Table 8.

TABLE 8.—*Showing the comparison, in atmospheres and tons per square inch, between the pressures actually observed in a close vessel, and those calculated from the formula* $p = p_0 \frac{(1 - \alpha\delta_0)}{\delta_0} \cdot \frac{\delta}{1 - \alpha\delta}$

1.	2.	3.	4.	5.	6.	7.
Density of products of combustion.	Value of p deduced from direct observation.	Value of p deduced from Equation (3) when $\alpha = \cdot 65$.	Value of p deduced from Equation (3) when $\alpha = \cdot 60$.	Value of p deduced from direct observation.	Value of p deduced from Equation (3) when $\alpha = \cdot 65$.	Value of p deduced from Equation (3) when $\alpha = \cdot 6$.
	Tons per sq. inch.	Tons per sq. inch.	Tons per sq. inch.	Atmospheres.	Atmospheres.	Atmospheres.
·05	0·70	·758	·855	107	115	130
·10	1·47	1·565	1·765	224	238	269
·15	2·33	2·432	2·734	355	370	416
·20	3·26	3·363	3·771	496	512	574
·25	4·26	4·367	4·879	649	665	743
·30	5·33	5·452	6·071	812	830	924
·35	6·49	6·628	7·350	988	1009	1119
·40	7·75	7·908	8·732	1180	1204	1330
·45	9·14	9·305	10·228	1392	1417	1557
·50	10·69	10·837	11·851	1628	1650	1805
·55	12·43	12·524	13·620	1893	1907	2074
·60	14·39	14·390	15·554	2191	2191	2369
·65	16·60	16·466	17·679	2528	2507	2692
·70	19·09	18·791	20·024	2907	2861	3049
·75	21·89	21·410	22·625	3333	3260	3445
·80	25·03	24·383	25·525	3812	3713	3887
·85	28·54	27·789	28·780	4346	4232	4383
·90	32·46	31·728	32·460	4943	4831	4943
·95	36·83	36·336	36·654	5608	5538	5582
1·00	41·70	41·698	41·477	6350	6350	6316

Now if the figures given in columns 2 and 5, being those derived from the observations themselves corrected by differencing, be compared with the values given in columns 3 and 6, computed on the value $\alpha = \cdot 65$ (that is, on the assumption that at the temperature of

explosion the liquid residue of 1 grm. of powder occupies ·65 c.c.), it will be found that the two columns are practically identical, thus affording a confirmation of the strongest nature of the correctness of our assumption. The closeness of agreement will be best seen by examining the graphical representations in Plate XIII. (p. 230). We have already, however, had more than once occasion to remark that there is reason to suppose that the observed pressures are slightly in defect, at all events at low densities. Other considerations have led us to the conclusion that a value of a not far removed from ·6 would more nearly represent the truth, were all disturbing influences removed. We have therefore added to the above table the pressures computed on this hypothesis; and Plate XIII. (p. 230), shows at a glance the comparison between the three curves.

(o) DETERMINATION OF THE TEMPERATURE OF EXPLOSION OF GUNPOWDER.

We are now in a position to compute the temperature of explosion.

Since p, v, and t are, in the case of permanent gases, connected by the equation of elasticity and dilatability,

$$pv = Rt \quad . \quad . \quad . \quad . \quad . \quad (5)$$

(where R is a constant and t is reckoned from absolute zero), t will be known if p, v, and R be known.

Now if we assume $a = {\cdot}6$, it follows that in the combustion of 1 grm. of powder (gravimetric density $= 1$) the gaseous products will, if the powder entirely fill the chamber in which it is placed, occupy a space of ·4 c.c. But we know that, at 0° Cent. and under a barometric pressure of 760 mm., the gaseous products of 1 grm. occupy a space of about 280 c.c. Hence at 0° Cent., if the gaseous products are compressed into a space of ·4 c.c., we have a pressure of 700 atmospheres; and since absolute zero $= -274°$ Cent., we have, in the equation $p_0 v_0 = Rt_0$, the values $p_0 = 700$, $v_0 = {\cdot}4$, $t_0 = 274$;

$$\therefore \qquad R = \frac{700 \times {\cdot}4}{274} = 1{\cdot}0218$$

Hence (5) becomes

$$pv = 1{\cdot}0218t \quad . \quad . \quad . \quad . \quad (6)$$

Now under the above conditions, but at the temperature of explosion, we have, from Table 8, $p = 6400$ atmospheres, and, as before, $v = {\cdot}4$.

Therefore

$$t = \frac{6400 \times \cdot 4}{1 \cdot 0218} = 2505 \quad . \quad . \quad . \quad (7)$$

and this is the temperature of explosion reckoned from absolute zero. Subtracting 274° from this temperature to reduce the scale to Centigrade, we have temperature of explosion = 2231° Cent.

If we assume $a = \cdot 65$, the temperature of explosion deduced in the same way would be 1950° Cent.; but this temperature, as we shall shortly show, would be somewhat too low.

We have now three points to consider:—

1. Is this temperature a probable one? and can any direct experimental facts be adduced to corroborate this theoretical deduction?

2. What is the mean specific heat of the solid or liquid products which the above temperature implies? and

3. Can any corroboration be given to the high rate of expansion of the solid residue implied by assuming the value of a as $= \cdot 6$?

With regard to the direct estimation of the temperature of explosion, we have made several experiments with the view of obtaining this result, by ascertaining the effects of the heat developed on platinum. For example, in Experiment 78 we introduced into the charge of R. F. G. a coil of very fine platinum wire and also a piece of thin sheet platinum. After the explosion the sheet platinum was found much bent, but unmelted; but on examination with a microscope there were evident signs of a commencement of fusion on the surface, and a portion of the fine platinum wire was found welded on to the sheet. The coil of wire was not to be found, but portions of it were observed welded to the sides of the cylinder.

Now we know that platinum is readily volatilised when exposed to the hydrogen-blowpipe at a temperature of about 3200° Cent., and therefore, if the temperature of explosion had approached this point, we should have expected the very fine wire to be volatilised; remembering the low specific heat of platinum, we should furthermore have been warranted in expecting more decided signs of fusion in the sheet metal.

Again, in Experiments 84, 85, and 68, pieces of platinum wire, ·03 inch (0·75 mm.) in diameter and 4 inches (100 mm.) long, were placed in the cylinder with considerable charges of R. L. G. and F. G. In none of these experiments did the platinum melt, although, as in the case of the sheet platinum, there were signs of fusion on

the surfaces of the wires. In Experiment 79, however, in which platinum wire was placed with a corresponding charge of the Spanish powder, the wire was fused, with the exception of a small portion. With this powder, indeed, which is of a very different composition from the English powders, and decidedly more rapidly explosive in its nature, it is quite possible that a somewhat higher heat may have been attained. But, as in one case the platinum wire was nearly fused, and in others it only showed signs of fusion, the conclusion we draw from the whole of these experiments on the fusion of the platinum is, that the temperature of explosion is higher than the melting-point of that metal, but not greatly so. Now, according to Deville, the melting-point of platinum is nearly 2000° Cent.; and hence we have a strong corroboration of the approximate accuracy of the theoretical temperature of explosion at which we have arrived, viz., 2231° Cent.

(*p*) MEAN SPECIFIC HEAT OF LIQUID PRODUCTS.

We have already given the specific heat of the liquid products when in the solid form. If we assume the temperature above specified to be correct, a mean specific heat of the liquid product of ·4090, or a total mean specific heat of the entire products of ·3094, would result, being an increment of about 67 per cent.; and this, judging from the analogy of the case we have cited, does not appear an improbable conclusion.

(*q*) PROBABLE EXPANSION OF NON-GASEOUS PRODUCTS BETWEEN ZERO AND TEMPERATURE OF EXPLOSION.

So far as we are aware, there were, prior to our experiments, no data existing as to the behaviour of the non-gaseous products of combustion at the high temperature involved, except perhaps the experiment made by Bunsen and Schischkoff, who exposed on platinum foil the solid residue in an oxyhydrogen jet, and concluded, from there being no ebullition, that at the temperature of 3300° Cent. the tension of the resulting vapour did not reach one atmosphere. Taking the circumstances into account, we may indeed doubt if the residue itself actually reached the temperature we have named; but the experiment would at all events prove that, at the temperature which we find to be that developed by explosion, the solid or liquid products are not in the state of vapour, or at least that the small portion volatilised had but an insignificant tension. To test, however, the behaviour of the

residue for ourselves, we placed in one of Siemens gas-furnaces, the temperature of which was estimated at about 1700° Cent., several crucibles containing powder-residue. The behaviour of the residue was in all cases the same; at first there was a little spirting (probably due to escape of water), which, however, soon diminished, and in time the contents of the crucibles became perfectly quiet, but up to the end of the experiment only a very slight volatilisation could be observed. In the case of three of the crucibles, two of which contained powder-residue, the other a mixture of potassium carbonate and liver of sulphur, when removed from the furnance after being exposed to the full heat for about a quarter of an hour, the volumes of the contents in the highly heated state were observed without difficulty. The contraction in cooling was evidently very great, especially at first. The contents set at a temperature of between 700° and 800° Cent., and when cool the expansion was measured by calibration with mercury. The first crucible gave an expansion of 77·8 per cent. between 0° Cent. and 1700° Cent.; the second (potass. carb. and liver of sulphur) an expansion of 93·3 per cent. The third (powder-residue) gave a considerably higher rate of expansion, above 100 per cent.; but we have not included the result, as, owing to the presence of a piece of platinum put in to test the temperature of the furnace, we were unable to make a very accurate measurement.

Of course the expansions, under the conditions we have just named, cannot be strictly compared with those which would have taken place in a close vessel under the high tension we know to exist; but they tend to confirm the results arrived at by a perfectly independent method. The experiments also show that, at a temperature approaching that developed by explosion, and under atmospheric pressure, the liquid products are still in that condition; and our experiments so far confirm those of Bunsen and Schischkoff to which we have alluded.

(r) OBSERVED PRESSURES IN THE BORES OF GUNS.

The data which we shall use for the discussion of the phenomena attending the combustion of gunpowder in ordnance are nearly entirely derived from the experiments carried on by the Committee on Explosives, under the presidency of Colonel Younghusband, F.R.S.

Two methods, of an entirely distinct nature, were employed by the Committee for the elucidation of the questions they had to consider.

One method consisted in determining the tension of the gas at various points in the bore, by direct measurement. The other mode consisted in measuring the time at which the projectile passed certain fixed points in the bore, thence deducing the velocities from the seat of the shot to the muzzle, and finally obtaining, by calculation, the gaseous pressure necessary to generate the observed velocities.

The apparatus used for determining the tension by direct measurement was the crusher-gauge, which we have already described; that for ascertaining the velocity was a chronoscope, specially designed for measuring very minute intervals of time. As the construction of this instrument has been fully explained elsewhere, we shall only here give a very general description of it.

Its most recent form is shown in plan and elevation in Plate XIV., Figs. 1 and 2 (p. 230). The mechanical part consists of a series of thin discs, A, A, etc., 36 inches in circumference, keyed on to a shaft, S, and made to rotate at a very high and uniform velocity through the train of wheels F, by means of a very heavy descending weight at B, arranged, to avoid an inconvenient length of chain, upon a plan originally proposed by Huyghens. This weight is continually wound up by means of the fly-wheel and handle at T. The stop-clock D, which can be connected or disconnected with the shaft E at pleasure, gives the precise speed of the circumference of the discs, which is usually arranged at about 1250 inches a second.

The recording arrangement is as follows:—Each disc is furnished with an induction-coil, G, the primary wire from which is conveyed to any point, K, in the gun where we may wish to record the instant at which the shot passes. There is at each such point a special contrivance, by which the shot in passing severs the primary wire, thereby causing a discharge from the secondary, which is connected with the discharger, Y. The spark records itself on the disc by means of paper specially prepared to receive it. The instrument is capable of recording the millionth part of a second, and, when in good working order, the probable error of a single observation should not exceed 4 or 5 one-millionths of a second.

The guns were arranged for the experiments as shown in Fig. 3 in the same plate. Holes were drilled in the powder-chamber in the positions marked A, B, C, and in the bore in the positions marked 1 to 18.

In A, B, and C, crusher-gauges were always placed; the holes, numbered 1 to 18, were fitted with crusher-gauges or the chronoscope-plugs at option.

It would be beside our object in this paper to enter into a discussion of the special experiments undertaken by the Committee on Explosives. The chief object of their investigations was to determine the nature of powder most suitable for use with heavy guns—that is to say, the powder which will allow of the highest effect being realised without unduly straining the structure within which the explosion is confined. A number of experiments were therefore made with powders of abnormal types, interesting and instructive only to artillerists; and these experiments will doubtless be fully reported on at a later date, by the proper authorities.

In our present paper we shall confine our attention chiefly, if not entirely, to the results obtained with the well-defined and well-known powders which have been admitted into the service for use with rifled guns, and which are known under the names of "Rifled Large Grain" and "Pebble." These powders are, moreover, the same as were used by us in our experiments in closed vessels, and therefore allow of a strict comparison with the tensions so obtained. But before giving the details, we cannot pass without notice certain differences in the results obtained by means of the two modes of experimenting to which we have alluded.

With pebble and other powders, where a slow and tolerably regular combustion takes place, the maximum tension of the gas, obtained both by direct measurement and by the chronoscope, agrees remarkably closely. There is generally a very slight difference indeed between the indicated pressures; but the case is greatly different where the powder is of a highly explosive or quickly burning description. In such a case, not only are the pressures indicated by the crusher-gauge generally much above those indicated by the chronoscope, but they differ widely in various parts of the powder-chamber, in the same experiment, and even in different parts of the same section of the bore. They are also locally affected by the form of the powder-chamber, and frequently indicate pressures considerably above the normal tensions that would be attained were the powder confined in a close vessel.

It is not difficult to explain these anomalies. When the powder is ignited comparatively slowly and tolerably uniformly, the pressure in the powder-chamber is also uniform, and approximates to that due to the density of the products of combustion.

The crusher-gauges, then, give similar results throughout the powder-chamber, and they accord closely with the results deduced from the chronoscope observations. But when a rapidly lighting or

"brisante" powder is used, the products of combustion of the portion first ignited are projected with a very high velocity through the interstices of the charge, or between the charge and the bore; and on meeting with any resistance their *vis viva* is reconverted into pressure, producing the anomalous local pressures to which we have drawn attention.

We have pretty clear proof that, when this intense local action is set up, the gases are in a state of violent disturbance, and that waves of pressure pass backwards and forwards from one end of the charge to the other, the action occasionally lasting the whole time that the shot is in the bore. In fact, with the rapidly burning, and in a less degree even with the slower burning powders, motion is communicated to the projectile not by a steady, gradually decreasing pressure like the expansive action of steam in a cylinder, but by a series of impulses more or less violent.

The time during which these intense local pressures act is of course very minute; but still the existence of the pressures is registered by the crusher-gauges. The chronoscopic records, on the other hand, which are, so to speak, an integration of the infinitesimal impulses communicated to the shot, afford little or no indication of the intensity of the local pressures, but give reliable information as to the *mean* gaseous pressure on the base of the shot.

The two modes of observation are, as we have elsewhere pointed out, complementary one to the other. The chronoscope gives no clue to the existence of the local pressures which the crusher-gauge shows to exist; while, on the other hand, where wave or oscillatory action exists, the results of the crusher-gauge cannot be at all relied on as indicating the mean pressure in the powder-chamber.

An interesting illustration of this distinction was afforded by two consecutive rounds fired from a 10-inch gun, in one of which wave-action was set up, in the other not. In both cases the projectile quitted the gun with the same velocity, and the mean pressure throughout the bore should of course have been the same. The chronoscopic records were, as they ought to be, nearly identical for the two rounds; but the pressures indicated by the crusher-gauge, were in the one round, at the points A, B, C, 1, 4 (Fig. 3, Plate XIV., p. 230), respectively 63·4, 41·6, 37·0, 41·9, and 25·8 tons on the square inch; in the other, at the same points, respectively 28·0, 29·8, 30·0, 29·8, and 19·8 tons on the square inch.

Where no wave-action exists, the chronoscopic pressures are generally somewhat higher than those of the crusher-gauge. The

difference is not generally greater than about 5 to 7 per cent., although, in the case of some exceptionally heavy shot, this variation was considerably exceeded. Among the causes tending to produce this difference may be cited:—1. Friction in the parts of the crusher-gauge. 2. Slight diminution of pressure due to windage.* 3. *Vis viva* of particles of the charge and products of combustion, a portion of which would be communicated to the shot, but would not take effect on the crusher-gauge. On the whole, however, the accordance of results derived from methods so essentially different was quite as close as could reasonably be expected, and entirely satisfactory.

We now pass to the consideration of the tensions actually found to exist in the bores of guns. Two series of experiments were made by the Committee on Explosives with the 10-inch 18-ton gun. The one series was with charges of 70 lbs. (31·75 kilos.) of pebble-powder. The weights of the shot were made to vary, the first rounds being fired with projectiles of 300 lbs. (136·05 kilos.), and the weights being successively increased to 350 lbs., 400 lbs., 450 lbs., 500 lbs., 600 lbs., 800 lbs., 1000 lbs., and concluding with projectiles of the weight of 1200 lbs. (544·20 kilos.).

In the other series, charges of 60 lbs. (27·21 kilos.) R. L. G. were used. The projectiles were of increasing weights, as above; but the experiments were not carried so far, the heaviest projectile in this series being of 600 lbs. (272 kilos.) weight.

As we shall have occasion more than once to refer to these experiments, and as the powder used was carefully selected to represent as nearly as possible the normal service-powder of each description, it appears to us convenient, in order to illustrate the methods followed in determining the powder-pressures, to take an example from each series.

This plan will further enable us to compare the difference of behaviour of pebble and R. L. G. powder in the bore of a gun.

Commencing, then, with the charge of 70 lbs. (31·75 kilos.) pebble-powder and the projectile of 300 lbs. (136·05 kilos.), the results given by the chronoscope, to which we shall turn our attention in the first instance, are given in Table 9.

In this table, column 1 gives the distances of the various plugs

* In the experiments with the 38-ton gun, an opportunity occurred of determining the differences in pressure due to the escape of the gases by the windage, and it was found that a reduction of windage of ·07 inch (1·75 mm.), *i.e.*, the difference between ·01 inch and ·08 inch windage, reduced the maximum pressure indicated by the crusher-gauge by about 1 ton per square inch. Of course the mean pressure on the base of the projectile was not reduced in anything like the same proportion.

from the seat of the shot in feet (see Fig. 3, Plate XIV., p. 230) (the distance from the seat of the shot to the bottom of the bore being 2 feet = ·610 metre). Column 2 gives the same distances in metres. Column 3 gives the observed time of passing each plug. Column 4 gives the corrected time from the commencement of motion, the time from the commencement of motion to first plug being interpolated. Column 5 gives the differences of time—that is, the time taken by the projectile to traverse the distance between the plugs. Column 6 gives the mean velocity of the projectile over the space between the plugs, in feet; and column 7 gives the same velocities in metres.

TABLE 9.—*Giving data obtained with chronoscope for calculating velocity and pressure in the bore of a* 10-*inch* 18-*ton gun. Charge,* 70 *lbs.* (31·75 *kilos.*) *pebble-powder. Weight of projectile,* 300 *lbs.* (136·05 *kilos.*). *Muzzle-velocity,* 1527 *feet* (465·4 *metres*).

1.	2.	3.	4.	5.	6.	7.
Distance from seat of shot.		Time observed at plugs.	Total time from seat of shot.	Time taken by shot to traverse distance between plugs.	Mean velocity over spaces between plugs.	
Feet.	Metres.	Seconds.	Seconds.	Seconds.	Feet per second.	Metres per second.
0·00	0·000	...	·000000			
				·002683	22	6·7
0·06	0·018	·000000	·002683			
				·001096	183	55·8
0·26	0·079	·001096	·003779			
				·000515	388	118·3
0·46	0·140	·001611	·004294			
				·000356	562	171·3
0·66	0·201	·001967	·004650			
				·000305	656	199·9
0·86	0·262	·002272	·004955			
				·000276	725	221·0
1·06	0·323	·002548	·005231			
				·000488	820	249·9
1·46	0·445	·003036	·005719			
				·000433	924	281·6
1·86	0·567	·003469	·006152			
				·000400	1000	304·8
2·26	0·689	·003869	·006552			
				·000375	1065	324·6
2·66	0·811	·004244	·006927			
				·000703	1138	346·9
3·46	1·055	·004947	·007630			
				·000658	1215	370·3
4·26	1·298	·005605	·008288			
				·000629	1273	388·0
5·06	1·542	·006234	·008917			
				·001192	1342	409·0
6·66	2·030	·007426	·010109			
				·001128	1418	432·2
8·26	2·518	·008554	·011237			

From these data are deduced, by correction and interpolation, the times given in Table 10, pp. 180 and 181. From the differences of the times are calculated the velocities, and from the velocities the pressures necessary to produce them are obtained.

We have not space within the limits of our paper to enter upon a discussion of the methods of calculation and correction necessary to arrive at the results tabulated; they are attended with very great labour, and a full consideration of the question would necessitate a

separate paper. As we shall hereafter show, it is not difficult, if we were to suppose the powder entirely converted into gas on the instant of explosion, to lay down the law according to which the pressure would vary in the bore of the gun; but the case under consideration is a much more complicated one. The charge of powder is not instantly exploded, but is generally ignited at a single point; the pressure (commencing at zero) goes on increasing at an extremely rapid rate until the maximum increment is reached. It still goes on increasing, but at a rate becoming gradually slower, until the maximum tension is reached, when the increase of density of the gas, aided by the combustion of the powder, is just counterbalanced by the decrease of density due to the motion of the projectile. After the maximum of tension is reached, the pressure decreases, at first rapidly, subsequently slower and slower.

If these variations in pressure be represented by a curve, it would commence at the origin convex to the axis of x, would then become concave, then again convex, and would finally be asymptotic to the axis of x.

In the same way, the curve representing the velocity would commence by being convex to the axis of abscissæ; it would then become concave, and, were the bore long enough, would be finally asymptotic to a line parallel to the axis of x.

The results of Table 10 are graphically represented in black lines in Plate XV. (p. 230), the space described by the shot being taken as the equicrescent or independent variable, and the two curves giving respectively the velocity and pressure at any point of the bore.

From the table (or curves) it will be seen that the maximum pressure attained by the powder is 18 tons per square inch (2745 atmospheres), and that this pressure is reached when the projectile has moved ·5 feet (·153 metre) and at ·00437 second from the commencement of motion.

The results given in the table have, as we have said, been arrived at by special methods of correction and interpolation; and their general correctness can be tested by examining whether a material alteration of pressure or velocity at any point can be made without seriously disturbing the times actually observed. It will be found that they cannot. But another question here presents itself for consideration. We have, in the curves on Plate XV. (p. 230), taken s as the independent variable; but if t were taken as the independent variable, and the relation between s and t were capable of being expressed by the explicit function $s=f(t)$, the velocity corresponding

TABLE 10.—*Giving the total time from commencement of motion, velocity, and tension of products of explosion, in bore of a 10-inch 18-ton gun, deduced from Table 9.*

Travel.		Time.		Velocity.		Pressure.	
		Total.	Over Intervals.				
Feet.	Metres.	Seconds.	Seconds.	Feet per second.	Metres per second.	Tons per square inch.	Atmospheres.
0·00	·000	·0000000	·0018182	11·0	3·35	1·723	262
0·02	·006	·0018182	·0005590	35·8	10·91	3·843	585
0·04	·012	·0023772	·0003058	65·4	19·93	6·096	928
0·06	·018	·0026330	·0002120	94·3	28·74	8·270	1259
0·08	·024	·0028950	·0001626	123·0	37·49	9·873	1503
0·10	·030	·0030576	·0001332	150·0	45·72	11·198	1705
0·12	·037	·0031908	·0001136	176·1	53·68	12·192	1857
0·14	·043	·0033044	·0000998	200·6	61·14	13·120	1998
0·16	·049	·0034042	·0000894	223·9	68·24	13·915	2119
0·18	·055	·0034936	·0000812	246·2	75·04	14·578	2220
0·20	·061	·0035748	·0000748	267·6	81·56	15·174	2311
0·22	·067	·0036496	·0000694	288·2	87·84	15·638	2381
0·24	·073	·0037190	·0000650	308·0	93·88	16·036	2442
0·26	·079	·0037840	·0000612	327·1	99·70	16·407	2498
0·28	·085	·0038452	·0000578	345·5	105·3	16·698	2543
0·30	·091	·0039030	·0000550	363·3	110·7	16·963	2583
0·32	·098	·0039580	·0000526	380·5	116·0	17·228	2623
0·34	·104	·0040106	·0000504	397·2	121·1	17·414	2652
0·36	·110	·0040610	·0000484	413·4	126·0	17·599	2680
0·38	·116	·0041094	·0000466	429·1	130·8	17·745	2702
0·40	·122	·0041560	·0000450	444·5	135·5	17·864	2720
0·42	·128	·0042010	·0000436	459·4	140·0	17·944	2733
0·44	·134	·0042446	·0000422	473·9	144·4	17·957	2734
0·46	·140	·0042868	·0000410	488·0	148·7	17·997	2741
0·48	·146	·0043278	·0000398	501·7	152·9	18·023	2745
0·50	·152	·0043676	·0000388	515·1	157·0	17·997	2741
0·52	·158	·0044064	·0000378	528·1	161·0	17·904	2726
0·54	·165	·0044442	·0000368	540·8	164·8	17·800	2711
0·56	·171	·0044810	·0001734	576·7	175·78	16·910	2575
0·66	·201	·0046544	·0001588	629·6	191·90	15·637	2381

0·76	·232	·0048132	·0001588	629·6	191·90	15·637	2381
0·86	·262	·0049614	·0001482	674·8	205·68	14·710	2240
0·96	·293	·0051013	·0001399	714·7	217·84	13·716	2089
1·06	·323	·0052347	·0001334	750·0	228·60	13·093	1994
1·16	·353	·0053625	·0001278	782·3	238·45	12·590	1917
1·26	·384	·0054856	·0001231	812·1	247·53	12·192	1857
1·36	·414	·0056047	·0001191	839·9	256·00	11·755	1790
1·46	·445	·0057202	·0001155	865·9	263·93	11·331	1725
1·56	·475	·0058325	·0001123	890·2	271·33	10·920	1663
1·66	·506	·0059420	·0001095	913·1	278·31	10·575	1610
1·76	·536	·0060490	·0001070	934·7	284·90	10·231	1558
1·86	·567	·0061537	·0001047	955·1	291·11	9·873	1503
1·96	·597	·0062562	·0001026	974·4	297·00	9·568	1457
2·06	·628	·0063570	·0001007	992·8	302·61	9·250	1409
2·16	·658	·0064560	·0000990	1010	307·85	8·972	1366
2·26	·689	·0065534	·0000974	1027	313·03	8·706	1326
2·36	·719	·0066493	·0000959	1043	317·91	8·442	1286
2·46	·750	·0067438	·0000945	1058	322·48	8·190	1247
2·56	·780	·0068371	·0000933	1072	326·75	7·952	1211
2·66	·811	·0069292	·0000921	1086	331·01	7·739	1178
2·76	·841	·0070201	·0000909	1100	335·28	7·541	1148
2·86	·871	·0071100	·0000899	1112	338·94	7·355	1120
2·96	·902	·0071989	·0000889	1125	342·90	7·183	1094
3·06	·932	·0072869	·0000880	1137	346·56	6·874	1047
3·46	1·054	·0076337	·0003468	1154	351·74	6·402	975
3·86	1·176	·0079685	·0003348	1195	364·24	5·911	900
4·26	1·298	·0082933	·0003248	1232	375·51	5·487	836
4·66	1·420	·0086097	·0003164	1265	385·57	5·089	775
5·06	1·542	·0089185	·0003088	1295	394·72	4·745	723
5·46	1·664	·0092209	·0003024	1322	402·95	4·453	678
5·86	1·786	·0095177	·0002968	1347	410·57	4·175	636
6·26	1·907	·0098093	·0002916	1371	417·88	3·936	599
6·66	2·029	·0100965	·0002872	1392	424·28	3·711	565
7·06	2·151	·0103797	·0002832	1412	430·38	3·526	537
7·46	2·273	·0106593	·0002796	1431	436·17	3·340	509
7·86	2·395	·0109357	·0002764	1448	441·35	3·168	482
8·26	2·517	·0112089	·0002732	1465	446·53		

to any value of t would be represented by the first derived function of $f(t)$, and the pressure by the second derived function. This, then, if a simple relation between s and t could be established, would be an easy method of treating the problem; but it has appeared to us practically impossible to obtain a single expression which shall represent the relation between s and t for the whole time occupied by the shot in its passage through the bore.

If, for example, we endeavoured to represent the relation between s and t by a linear equation of the form

$$s = at + bt^2 + ct^3 + dt^4, \text{ etc.} \qquad (8)$$

we should have to determine the most probable values of the coefficients a, b, c, d, etc., from the eighteen to twenty direct observations connecting s and t. The equation would further have to be such that the first and second derived functions should represent curves of the general nature we have described. It is obvious that, setting all other consideration aside, the labour of such a series of calculations would be insurmountable.

But although it is impossible to obtain a single relation between s and t for the whole length of the bore, we have endeavoured, on account of the great importance of the question, to obtain such a relation for the commencement of motion, where the question of pressure is of vital importance.

To do this, we have taken only the observed values of s and t so far that we could be certain the position where the maximum pressure was attained was included, but have made no assumption whatever as to the actual position of maximum pressure.

We then assumed that the relation between s and t was capable of being expressed by an equation of the form

$$s = a\, t^{\alpha + \beta t + \gamma t^2} \qquad (9)$$

and from the observed values of s and t the probable values of a, α, β, γ were computed by the method of least squares.

Treating in this manner the experiment under discussion, and taking from Table 9 the first six values of s and t,* we have obtained for the most probable values of

$$a = 3{\cdot}31076$$
$$\alpha = 1{\cdot}37851$$
$$\beta = {\cdot}76600$$
$$\gamma = -{\cdot}06932$$

* For the convenience of calculation, the unit of time used is not a second but the thousandth part of a second. The unit of space is altered in like proportion.

and for the relation between s and t the equation

$$s = 3{\cdot}31076t^{1{\cdot}37851 + {\cdot}76600t - {\cdot}06932t^2} \quad . \quad . \quad . \qquad (10)$$

By differentiation, we obtain for the velocity

$$\frac{ds}{dt} = v = \frac{s}{t}\{(\alpha + \beta t + \gamma t^2).(1 + \log_e t) - (\alpha - \gamma t^2).\log_e t\} \qquad (11)$$

and by a second differentiation,

$$\begin{aligned} \text{pressure T} &= \frac{w}{g}\cdot\frac{d^2s}{dt^2} \\ &= \frac{w}{g}\cdot\frac{v}{t}\{(\alpha + \beta t + \gamma t^2)(1 + \log_e t) - (\alpha - \gamma t^2)\log_e t - 1\} \\ &+ \frac{w}{g}\cdot\frac{s}{t}\{\beta + (\beta - 4\gamma t).(1 + \log_e t)\} \quad . \quad . \quad . \qquad (12) \end{aligned}$$

Table 11, p. 184, gives the results of the calculations necessary for obtaining the values of s, v, and T from Equations (10), (11), and (12).

To avoid repetition, we have introduced in this table the following abbreviations:—

$$\left.\begin{aligned} \mathrm{M} &= \alpha + \beta t + \gamma t^2 \\ \mathrm{N} &= \alpha - \gamma t^2 \\ \mathrm{P} &= \mathrm{M}(1 + \log_e t) - \mathrm{N}\log_e t \\ \mathrm{P}' &= \beta + (\beta + 4\gamma t).(1 + \log_e t) \end{aligned}\right\} \quad . \quad . \quad . \qquad (13)$$

and the values furnished in Table 11 can be compared with those given in Table 10.

But the comparison, both as to velocity and pressure, can be more readily seen by a graphical representation; and we have accordingly laid down in Plate XV. (p. 230), in full black lines, the curves of velocity and pressure taken from Table 10.

The results of Table 10 have already been graphically represented in Plate XVI. (p. 230); but in Plate XVI. (p. 230), t instead of s is taken as the independent variable, with the view of enabling the accordance of the methods to be more easily compared. The curves in dotted lines indicate the velocity and pressure shown in Table 11, and deduced from formulæ (10), (11), and (12).

It will be observed that the two curves of velocity approximate exceedingly closely. The difference between the pressure-curves also is not greater than might be expected; and the difference, such as it is, is due to our not having succeeded in obtaining an equation which represents the corresponding observed values of s and t so closely as do the values given in Table 10.

TABLE 11.—*Giving the results of the calculations necessary in order to obtain the values of* s, v, *and* T *from Equations* (10), (11), *and* (12). *Pebble-powder.*

t.	M.	s.	$\frac{s}{t}$	N.	$1+\log_e t$.	$M(1+\log_e t)$ $-N\log_e t$.	v.	$\frac{v}{t}$	$(P-1)\frac{v}{t}$	P′.	$P' \cdot \frac{s}{t}$	$\frac{d^2s}{dt^2}$	Pressure (T). Tons per sq. inch.	Pressure (T). Atmospheres.
2·8	2·979805	71·183	25·422	1·922018	2·029619	4·068930	103·430	36·939	113·3533	·744811	18·9346	132·2879	7·036	1071
3·0	3·052588	94·706	31·568	2·002435	2·098612	4·206297	132·784	44·261	141·9139	·627702	19·8142	161·7281	8·601	1310
3·2	3·119825	124·712	38·972	2·088397	2·163151	4·319539	172·661	53·956	179·1090	·503480	19·6216	198·7306	10·569	1609
3·4	3·181516	162·495	47·792	2·179906	2·223775	4·409265	210·632	61·950	211·0801	·372791	17·8164	228·8965	12·174	1854
3·5	3·210283	184·734	52·781	2·227741	2·252763	4·441170	234·409	66·974	230·4589	·305200	16·1088	246·5677	13·113	1997
3·6	3·237662	209·423	58·175	2·276961	2·280934	4·468253	259·940	72·205	250·4252	·236186	13·7404	264·1656	14·049	2139
3·7	3·263655	236·775	63·993	2·327569	2·308333	4·488377	287·224	77·628	270·7957	·165811	10·6107	281·4064	14·966	2279
3·8	3·288261	266·929	70·245	2·379563	2·335001	4·501375	316·427	83·270	291·5595	·094127	6·6122	298·1717	15·857	2415
3·9	3·311482	300·064	76·940	2·432943	2·360977	4·507152	346·780	88·917	311·8354	·021182	1·6296	313·4650	16·671	2539
4·0	3·333314	336·344	84·086	2·487710	2·386294	4·505557	378·854	94·713	332·0218	·052975	4·4549	327·5669	17·421	2653
4·1	3·353761	375·876	91·678	2·543863	2·410987	4·496518	412·222	100·542	351·5469	·128309	11·7622	339·8027	18·071	2752
4·2	3·372821	418·730	99·698	2·601303	2·435085	4·479017	446·549	106·321	369·8926	·204773	20·4152	349·4774	18·586	2830
4·3	3·390496	465·270	108·225	2·660328	2·458615	4·455537	482·200	112·139	387·4905	·282331	30·5552	356·9353	18·983	2891
4·4	3·406782	515·254	117·105	2·720641	2·481605	4·423368	517·999	117·727	403·0228	·360949	42·2690	360·7538	19·186	2922
4·5	3·421684	568·847	126·411	2·782341	2·504077	4·383297	554·097	123·133	416·5855	·440591	55·6953	360·8902	19·193	2923
4·6	3·435198	626·093	136·104	2·845426	2·526056	4·335222	590·041	128·270	427·8089	·521230	70·9415	356·8674	18·978	2890
4·7	3·447326	686·871	146·142	2·909898	2·547563	4·279037	625·347	133·052	436·2824	·602829	88·0988	348·1836	18·517	2820
4·8	3·458067	751·087	156·477	2·975758	2·568616	4·214629	659·492	137·394	441·6707	·685373	107·2436	334·4271	17·786	2709
4·9	3·467422	818·733	167·087	3·043003	2·589535	4·142050	692·082	141·241	443·7863	·769002	128·4899	315·2964	16·769	2554
5·0	3·475390	889·447	177·890	3·111635	2·609438	4·060823	722·380	144·476	442·2155	·853158	151·7686	290·4469	15·447	2352
5·1	3·481972	963·090	188·841	3·181653	2·629241	3·971264	749·937							
5·2	3·487167	1039·290	199·865	3·253058	2·648659	3·873138	774·104							

The pressures given by the crusher-gauges (which can be compared with those given in either of the Tables 10 or 11) at the points A, B, C, 1, 4, are respectively 17·2, 15·6, 15·6, 12·8, and 11·1 tons per square inch; or in atmospheres, 2169, 2376, 2376, 1949, and 1690.

We now pass to the consideration of the results furnished by R. L. G. powder. Taking, as in the case of pebble-powder, the particular set of experiments where shot of 300 lbs. (136·05 kilos.) were used, the data furnished by the chronoscope are given in Table 12.

TABLE 12.—*Giving data obtained with chronoscope for calculating the velocity and pressure in the bore of a 10-inch 18-ton gun. Charge,* 60 *lbs.* (27·2 *kilos.*) *R. L. G. Weight of projectile,* 300 *lbs.* (136·05 *kilos.*).

Distance from base of shot.		Time observed at plugs.	Total time from seat of shot.	Time taken by shot to traverse distance between plugs.	Mean velocity over spaces between plugs.	
Feet.	Metres.	Seconds.	Seconds.	Seconds.	Feet per second.	Metres per second.
0·00	0·000	...	·000000	·000767	78·2	23·8
0·06	0·018	·000000	·000767	·000596	336	102·4
0·26	0·079	·000596	·001363	·000411	488	148·7
0·46	0·140	·001007	·001774	·000316	633	192·9
0·66	0·201	·001323	·002090	·000278	719	219·1
0·86	0·262	·001601	·002368	·000255	781	238·0
1·06	0·323	·001856	·002623	·000469	855	260·6
1·46	0·445	·002325	·003092	·000430	935	285·0
1·86	0·567	·002755	·003522			

From these data, in the same manner as in the case of pebble-powder, are calculated the velocities and pressures exhibited in Table 13, p. 186.

The velocity and pressure obtained with the R. L. G. powder are graphically represented by the dotted curves in Plate XV. (p. 230); and by comparing these with the similar curves furnished by pebble-powder, the advantages obtained by the use of the slow-burning pebble-powder are clearly seen.

Thus it will be observed that the muzzle-velocity obtained with the pebble-powder is 1530 feet (466·3 metres), while the maximum pressure in the bore is 18 tons per square inch (2745 atmospheres). The velocity given by the R. L. G. powder is, on the other hand, only 1480 feet (451·1 metres), while the maximum pressure is 22·07 tons per square inch (3360 atmospheres).

Table 13.—*Giving the total time from commencement of motion, velocity, and tension of products of explosion in bore of* 10-*inch* 18-*ton gun, deduced from Table* 12.

Travel.		Time.		Velocity.		Pressure.	
		Total.	Over Intervals.				
Feet.	Metres.	Seconds.	Seconds.	Feet per second.	Metres per second.	Tons per sq. inch.	Atmospheres.
0·00	·000	·0000000	·0005164	38·7	11·80	7·950	1211
0·02	·006	·0005164	·0001451	137·8	42·00	21·204	3229
0·04	·012	·0006615	·0001059	188·8	57·55	22·065	3360
0·06	·018	·0007674	·0000874	228·7	69·71	22·039	3356
0·08	·024	·0008548	·0000762	262·5	80·01	21·999	3350
0·10	·030	·0009310	·0000684	292·2	89·06	21·840	3326
0·12	·037	·0009994	·0000627	318·9	97·20	21·628	3293
0·14	·043	·0010621	·0000583	343·3	104·64	21·403	3259
0·16	·049	·0011204	·0000546	365·7	111·46	21·138	3219
0·18	·055	·0011750	·0000517	386·6	117·83	20·767	3162
0·20	·061	·0012267	·0000493	405·9	123·72	20·276	3088
0·22	·067	·0012760	·0000471	423·9	129·20	19·746	3007
0·24	·073	·0013231	·0000454	440·6	134·29	19·216	2926
0·26	·079	·0013685	·0000438	456·4	139·11	18·713	2850
0·28	·085	·0014123	·0000424	471·2	143·62	18·249	2779
0·30	·091	·0014547	·0000412	485·3	147·92	17·851	2718
0·32	·098	·0014959	·0000401	498·7	152·00	17·440	2656
0·34	·104	·0015360	·0000391	511·4	155·87	17·096	2603
0·36	·110	·0015751	·0000381	523·7	159·62	16·778	2555
0·38	·116	·0016132	·0000373	535·4	163·19	16·499	2512
0·40	·122	·0016505	·0000365	546·8	166·66	16·261	2476
0·42	·128	·0016870	·0000359	557·7	169·99	16·036	2442
0·44	·134	·0017229	·0000351	568·4	173·25	15·863	2416
0·46	·140	·0017580	·0000345	578·7	176·39	15·691	2389
0·48	·146	·0017925	·0000339	588·8	179·46	15·558	2369
0·50	·152	·0018264	·0000334	598·5	182·42	15·439	2351
0·52	·158	·0018598	·0000329	608·1	185·35	15·320	2333
0·54	·165	·0018927	·0000323	617·5	188·21	15·201	2315
0·56	·171	·0019250	·0001552	644·3	196·38	14·700	2238
0·66	·201	·0020802	·0001460	684·9	208·76	14·286	2175
0·76	·232	·0022262	·0001387	721·0	219·76	13·451	2048
0·86	·262	·0023649	·0001327	753·5	229·66	12·722	1937
0·96	·293	·0024976	·0001277	783·1	238·69	12·060	1836
1·06	·323	·0026253	·0001234	810·1	246·92	11·384	1734
1·16	·353	·0027487	·0001198	834·8	254·44	10·774	1641
1·26	·384	·0028685	·0001166	857·6	261·39	10·204	1554
1·36	·415	·0029851	·0001138	878·7	267·83	9·701	1477
1·46	·445	·0030989	·0001113	898·2	273·77	9·210	1402
1·56	·475	·0032102	·0001091	916·3	279·29	8·720	1328
1·66	·506	·0033193	·0001071	933·2	284·44	8·296	1263
1·76	·536	·0034264	·0001054	949·1	289·28	7·885	1201
1·86	·567	·0035318					

If, as in the case of pebble-powder, we express for the first instants of motion the relation between s and t by an equation of the form of that given in (9), we obtain

$$s = \cdot 57837 t^{3\cdot 42802 - \cdot 02336 t + \cdot 000245 t^2} \quad . \quad . \quad (14)^*$$

* In this equation and Table 14, the unit of time is, for convenience, the one ten-thousandth part of a second.

and the values of s, v, T corresponding to those of t are given in the scheme shown in Table 14, p. 188.

The results of Table 14, in comparison with those of the other mode of calculation (Table 13), are graphically compared in Plate XVII. (p. 230). It will be observed that, as in the case of pebble-powder, the two methods give values closely accordant; and if Plate XVII. (p. 230) be compared with Plate XVI. (p. 230), the differences in velocity and pressure at the commencement of motion between the two natures of powder are very strikingly shown. Thus it will be observed that with pebble-powder the maximum pressure, 2745 atmospheres, is reached when the projectile has moved ·5 foot (·152 metre), and at about ·00437 second after the commencement of motion. With R. L. G. powder the maximum pressure, 3365 atmospheres, is reached when the projectile has moved only ·05 foot (·015 metre), and at about ·00070 second from the commencement of motion. The first foot of motion is, with the one powder, traversed in about ·0025 second, with the other in about ·0051 second.

The pressure given by the crusher-gauges in the experiments with R. L. G. under discussion (and these pressures should be compared both with those given in Table 13 and with the crusher-gauge pressures furnished at the same points by pebble-powder) were, at A, B, C, 1, and 4, respectively 44·2, 30·3, 22·5, 13·5, 12 tons per square inch; or, in atmospheres, 6731, 4614, 3426, 2056, and 1827.

In deducing the pressure from the velocity, we of course assumed that the gaseous products of combustion acted on the projectile in the manner in which gases are generally assumed to act.

. With the slower-burning powders this hypothesis appears to be not far from the truth; but with the more explosive powders the crusher-gauges show that the powder acts on the shot, as we have already observed, by a succession of impulses; and in this case the curve of pressures derived from the chronoscopic observations must be taken to represent the mean pressures acting on the projectile throughout the bore.

With the various powders experimented on by the Committee on Explosives, there have of course been very great variations in the pressures indicated.

The highest mean pressure indicated by the chronoscope was 30·6 tons, 4660 atmospheres; and this pressure was attained with a charge of 60 lbs. R. L. G., and a projectile weighing 400 lbs. In the same series, the highest local or wave-pressure exhibited by the crusher-gauges was 57·8 tons, 8802 atmospheres; but this excessive pressure

TABLE 14.—*Giving the results of the calculations for determining the values of* s, v, *and* T *from Equations* (14), (11), *and* (12). *R. L. G. powder.*

t.	M.	s.	$\frac{s}{t}$	N.	$1+\log_e t$.	$M(1+\log_e t)$ $-N\log_e t$.	v.	$\frac{v}{t}$	$(P-1)\frac{v}{t}$	P'.	$P'.\frac{s}{t}$	$\frac{d^2s}{dt^2}$	Pressure (T). Tons per sq. inch.	Atmospheres.
2	3·38228	6·03	3·015	3·42704	1·69315	3·35125	10·104	5·052	11·8785	·05959	·1797	11·699	6·22	947
4	3·33850	59·18	14·795	3·42410	2·38629	3·21983	47·637	11·909	26·4360	·06975	1·0320	25·404	13·51	2057
6	3·29667	212·57	35·430	3·41920	2·79176	3·07713	109·023	18·170	37·7415	·07216	2·5566	35·185	18·71	2849
8	3·25681	505·13	63·141	3·41234	3·07944	2·92339	184·586	23·073	44·3784	·07115	4·4925	39·886	21·21	3230
8·5	3·24715	602·79	70·918	3·41032	3·14007	2·89796	205·517	24·178	45·8889	·07055	5·0036	40·885	21·74	3311
9	3·23762	710·70	78·965	3·40818	3·19722	2·86286	226·066	25·118	46·7913	·06985	5·5157	41·276	21·95	3342
9·5	3·22820	828·89	87·251	3·40591	3·25129	2·82812	246·756	25·974	47·4836	·06904	6·0238	41·460	22·04	3356
10	3·21891	957·45	95·745	3·40352	3·30258	2·79383	267·495	26·750	47·9850	·06814	6·5241	41·461	22·04	3356
11	3·20069	1245·60	113·200	3·39838	3·39790	2·72665	308·657	28·060	48·4498	·06611	7·4837	40·966	21·79	3318
12	3·18297	1574·70	131·23	3·39274	3·48491	2·66171	349·296	29·191	48·5070	·06378	8·3712	40·136	21·35	3251
13	3·16573	1943·80	149·52	3·38662	3·56495	2·59916	388·626	29·894	47·8053	·06122	9·1536	38·652	20·56	3131
14	3·14899	2351·53	167·97	3·38000	3·63906	2·53934	426·533	30·466	46·8988	·05844	9·8160	37·082	19·72	3003
15	3·13273	2796·30	186·42	3·37290	3·70805	2·48234	462·758	30·851	45·7312	·05547	10·3406	35·391	18·82	2866
16	3·11696	3276·45	204·78	3·36530	3·77259	2·42841	497·290	31·081	44·3964	·05233	10·7161	33·680	17·91	2727
17	3·10169	3790·33	222·96	3·35722	3·83321	2·37772	530·136	31·184	42·9638	·04904	10·9341	32·029	17·03	2593
19	3·07263	4913·00	258·57	3·33958	3·94444	2·28661	591·249	31·118	40·0375	·04206	10·8759	29·161	15·51	2362
21	3·04551	6152·37	292·97	3·31998	4·04452	2·20988	647·429	30·830	37·3006	·03460	10·1368	27·164	14·44	2199
23	3·02035	7500·70	326·12	3·29842	4·13549	2·14846	700·656	30·463	34·9857	·02675	8·7236	26·262	13·97	2127
25	2·99715	8954·50	358·18	3·27490	4·21888	2·10311	753·292							
27	2·97591	10515·00	389·45	3·24942	4·29584	2·07446	807·898							

was exhibited only in the crusher marked A in Plate XIV., Fig. 3 (p. 230), and was probably confined to that particular point. The pressures exhibited by the same powder in the same round, at the points B and C in the powder-chamber, were respectively 37 tons, 5634 atmospheres; and 29·6 tons, 4507 atmospheres.

But although, in the various guns and with the various charges and special powders experimented with, the pressures at different points of the bore exhibit, as might be expected, marked differences, these differences almost altogether disappeared when powders of normal types and uniform make were experimented with, and when the pressure was referred, not to fixed positions in the bore of the gun, but to the density of the products of combustion.

We have already referred to the experiments made with cylinders gradually increasing in weight in the 10-inch gun. A similar series was made in the 11-inch gun with charges of powder of 85 lbs. (38·56 kilos.); and as the series in both guns were made with great care and under as nearly as possible the same conditions, we selected, in the first instance, the experiments with pebble-powder in these guns, to test the accordance or otherwise of the tensions, under the varied conditions of experiment, when taken simply as functions of the density.

The results of these calculations are graphically represented in curves 1 and 2, Plate XVIII. (p. 230); and it will be observed that with these different calibres and charges the tensions developed are as nearly as possible identical.

Curves 3 and 4 on the same plate exhibit the results of similar calculations for 60 lbs. R. L. G. fired in the 10-inch gun, and 30 lbs. R. L. G. fired in the 8-inch gun. In this case also, although there are differences between the curves representing the pebble and R. L. G. powders, to which we shall allude further on, the accordance between the same description of powder fired from the different guns is almost perfect.

(*s*) EFFECT OF INCREMENTS IN THE WEIGHT OF THE SHOT ON THE COMBUSTION AND TENSION OF POWDER IN THE BORE OF A GUN.

In our preliminary sketch of the labours of previous investigators, we alluded to the views held by Robins and Rumford upon the rapidity of combustion within the bore. The latter, relying chiefly upon the fact that powder, especially when in very large grains, was frequently blown unburned from the muzzle, concluded that the com-

bustion was very slow. Robins, on the other hand, considered that, with the powder he employed, combustion was practically completed before the shot was materially displaced; and it is not easy to see why the unanswerable (if correct) and easily verified fact of which he makes use has received so little attention from artillerists.

Robins, it will be remembered, argues that if, as some assert, a considerable time is consumed in the combustion of the charge, a much greater effect would be realised from the powder where heavier projectiles were used, but that such is not the case.

The Committee on Explosives have completely verified the correctness of Robins' views.

In the 10-inch gun, with a charge of 60 lbs. (27·2 kilos.) R. L. G. powder, the work realised from the powder is only increased by about 5 per cent. when the weight of shot is doubled.

In the slower-burning pebble-powder, with a charge of 70 lbs. (31·75 kilos.), with a similar increase in the shot, the greater effect realised was about 8½ per cent.; but when the weight was again doubled (that is, increased to four times the original weight), the additional effect was barely 1 per cent.

Piobert's views, moreover, that the pressure exercises but a trifling influence upon the rate of combustion, appears to us entirely untenable. With a particular sample of service pebble-powder, we found the time required for burning a single pebble in the open air to be about 2 seconds. The same sample was entirely consumed in the bore of a 10-inch gun, and must therefore have been burned in less than ·009 second.

(*t*) EFFECT OF MOISTURE UPON THE COMBUSTION AND TENSION OF POWDER.

It is perhaps unnecessary to say that we do not share the views of those who consider that the presence of water in powder may increase the tension of the products of explosion. We have made no experiments upon this head in closed vessels; but the following table exhibits the effect of moisture in gunpowder upon the velocity of the projectile and the tension of the gas when the powder is fired in a gun, the proportions of moisture varying from 0·7 to 1·55 per cent. The powder from which these results were obtained, was pebble, carefully prepared by Colonel Younghusband, and was the same in all respects, except as regards the quantity of moisture.

TABLE 15.—*Showing the effect of moisture in the powder upon the velocity of the projectile and pressure of the gas.*

Percentage of Moisture.	Velocity.		Maximum Pressures.	
	Feet	Metres.	Tons per square inch.	Atmospheres.
0·70	1545	470·92	22·02	3353
0·75	1541	774·50	21·70	3304
0·80	1537	468·47	21·38	3256
0·85	1533·5	467·41	21·07	3208
0·90	1530	466·34	20·77	3163
0·95	1526·5	465·30	20·47	3117
1·00	1523·5	464·40	20·18	3073
1·05	1520·5	463·44	19·90	3030
1·10	1517·5	462·53	19·63	2989
1·15	1514·5	461·61	19·37	2949
1·20	1512	460·85	19·12	2911
1·25	1509·5	460·10	18·87	2873
1·30	1507	459·33	18·63	2837
1·35	1504·5	458·60	18·40	2802
1·40	1502	457·80	18·18	2768
1·45	1499·5	457·04	17·97	2736
1·50	1497·5	456·43	17·76	2704
1·55	1495·5	455·82	17·55	2672

From this table it will be seen that, by the addition of considerably less than 1 per cent. of moisture, the muzzle-velocity is reduced by about 60 feet, and the maximum pressure by about 20 per cent., pointing obviously to a much more rapid combustion in the case of the drier powder.

(*u*) LOSS OF HEAT BY COMMUNICATION TO THE ENVELOPE IN WHICH THE CHARGE IS EXPLODED.

We have now given a hasty sketch of the means that have been adopted to determine the pressures actually existing in the bores of guns, and of the general results we have arrived at; and before proceeding to the theoretical consideration of the relation which should then exist between the tension and the density of the gases, we must direct attention to an important point—and that is, "what loss of heat do the gases suffer? or, in other words, what proportion of energy in the powder is wasted by communication to the envelope in which the powder is fired, that is, to the barrel of the gun?"

Every one is aware that if a common rifled musket be very rapidly fired, as may easily now be done by the use of breech-loading arms, the barrel becomes so hot that it cannot be touched with the

naked hand with impunity, and, even with a field-gun, the increment of heat due to a few rounds is very considerable.

So far as we know, the Count de Saint-Robert* made the first attempt to determine the amount of heat actually communicated to a small arm.

De Saint-Robert made three series of experiments with service rifled muskets, firing the ordinary charge of 4·5 grms. In the first series, the muskets were loaded in the usual manner; in the second series, the ball was placed near the muzzle; in the third, the muskets were loaded with powder alone. The results at which De Saint-Robert arrived, and which are not difficult to explain, were, that the greatest quantity of heat was communicated to the musket when the ball was placed near the muzzle, that the quantity communicated when no projectile at all was used, stood next in order, and that least heat was communicated when the musket was loaded in the usual manner.

He further found that the quantity of heat communicated in this last case, with the powder and arm used, was about 250 grm.-units per grm. of powder fired.

We found ourselves unable, however, to adopt Count de Saint-Robert's important results for the guns and charges we have been considering, because conclusions derived from small arms could hardly be applied to large ordnance without modification.

We therefore instituted the experiments described under Nos. 72 and 73. The gun used was a 12-pr. B.L., and in the first Experiment (No. 72) nine rounds were fired with $1\frac{3}{4}$ lb. (794 grms.) and a projectile weighing nearly 12 lbs. (5330 grms.).

Prior to the rounds being fired, arrangements were made for placing the gun, whenever the series should be concluded, in a vessel containing a given weight of water; and before the experiment was commenced the gun and water were brought to the same temperature, and that temperature carefully determined.

After the firing, the gun was placed in the water, and the rise of temperature due to the nine rounds determined. This rise was found to be equivalent to 236,834 grms. of water raised through 2°·305 Cent., or the heat communicated to the gun by the combustion of 1 grm. of the charge was equal to 76·4 grm.-units.

Of course an addition has to be made to this number, on account both of some loss of heat in the determination and of the unavoidable loss of heat between the rounds.

* *Traité de Thermodnamique* (Turin, 1865), p. 120.

The second Experiment (No. 73) was made with five rounds of $1\frac{1}{2}$ lb. (680·4 grms.) of the same powder with the same weight of projectile. The heat communicated to the gun by the five rounds was, when expressed in water, sufficient to raise 112,867 grms. through $2^{\circ}\cdot694$ Cent., or 1 grm. of the charge, in burning, communicated to the gun 89·4 grm.-units of heat.

Considering the difficulty, in an experiment of this nature, of avoiding a considerable loss from radiation, conduction, and other causes, we do not think we shall be far wrong in assuming that in the case of the 12-pr. B.L. gun, fired under the conditions named, the heat communicated to the gun is about 100 grm.-units for each gramme of powder exploded.

To arrive at the amount of heat communicated to the gun when still larger guns are employed, there are two principal points to be considered—1st, the ratio which the amount of the surface bears to weight of the charge exploded; and 2nd, the time during which the cooling effect of the bore operates upon the products of explosion. The first of these data is of course exactly known, and from our experiments the second is also known with very considerable exactness. Computing, therefore, from the data given by the 12-pr., the loss of heat suffered by the gases in the 10-inch gun, we find that loss to be represented by about 25 grm.-units; and hence we find that the quantity of work in the form of heat communicated to the gun varies approximately from 250 grm.-units per grm. of powder in the case of a rifled musket, to 25 grm.-units in the case of a 10-inch gun.

Similar considerations lead us to the conclusion that in a close vessel such as we employed for explosion, *when filled with powder*, the loss of pressure due to the communication of heat to the envelope would not amount to 1 per cent. of the total pressure developed.

(v) PRESSURE IN THE BORES OF GUNS, DERIVED FROM THEORETICAL CONSIDERATIONS.

We now pass to the theoretical consideration of the question. Suppose the powder to be fired, as is the case in the chamber of a gun, and suppose, further, that the products of combustion are allowed to expand, what will be the relation between the tension of the gases and the volume they occupy throughout the bore?

For the sake of simplicity, we shall, in the first instance, assume that the gravimetric density of the powder is unity, that the powder

fills completely the space in which it is placed, that the whole charge is exploded before the projectile is sensibly moved from its initial position, and that the expansion takes place in a vessel impervious to heat.

In our preliminary sketch we alluded to the results of Hutton's investigations as to the relations existing between the density and tension of the gases and the velocity of the projectile at any point of the bore. Hutton, however, assumed that the tension of the inflamed gases was directly proportional to their density, and inversely as the space occupied by them. In other words, he supposed that the expansion of the gases, while doing work both on the projectile and on the products themselves, was effected without loss of heat.

Recent research, which has demonstrated that no work can be effected by the expansion of gases without a corresponding expenditure of heat, has enabled modern artillerists to correct Hutton's assumption; and the question of the pressure exercised and work performed by gunpowder in the bore of a gun has been examined both by Bunsen and Schischkoff, and by the Count de Saint-Robert.*

De Saint-Robert, like Hutton, supposed that the whole of the products of the explosion were, on ignition, in a gaseous state, and that hence the relation between the pressure and the volume of the products followed from the well-known law connecting the tension and volume of permanent gases.

Bunsen and Schischkoff, on the other hand, who, like ourselves, have arrived at the conclusion that at the moment of explosion a large part of the products is not in the gaseous state, have deduced the total work which gunpowder is capable of performing, on the assumption that the work on the projectile is effected by the expansion of the permanent gases alone, without addition or subtraction of heat, and that, in fact, the non-gaseous products play no part in the expansion.

Sufficient data were not at the command of either of the authorities we have named, to enable them adequately to test their theories; and we propose in the first place, with the data at our disposal, to compare their hypothesis with actual facts, by computing the tensions for different volumes and comparing the calculated results, both with the tensions in a close vessel and with those derived from actual experiments in the bores of guns.

Assuming, in the first place, with De Saint-Robert, that the whole of the products are in the gaseous form,—

* *Traité de Thermodynamique*, p. 154.

Let p be the value of the elastic pressure of the permanent gases generated by the combustion of the powder corresponding to any volume v, and let p_0, v_0 be the known initial values of p and v. Let also C_p be the specific heat of these gases at constant pressure, and C_v be the specific heat at constant volume. Then, from the well-known relation existing between p and v, where a permanent gas is permitted to expand in a vessel impervious to heat, we have

$$p = p_0\left(\frac{v_0}{v}\right)^{\frac{C_p}{C_v}} \quad . \quad . \quad . \quad . \quad (15)$$

and this equation, upon De Saint-Robert's hypothesis, expresses the relation between the tension of the gases and the volume occupied by them in the bore of a gun.

Taking p_0 from Table 8, at 41·477 tons per square inch, and assuming at unity the space v_0 occupied by the charge when at a gravimetric density of 1, taking, further, the value of $\frac{C_p}{C_v} = 1{\cdot}41$ as computed by De Saint-Robert, Equation (15) becomes

$$p = 41{\cdot}477\left(\frac{1}{v}\right)^{1{\cdot}41} \quad . \quad . \quad . \quad . \quad (16)$$

If we now take Bunsen and Schischkoff's view, that a portion only of the products is in the form of permanent gases, and that they expand without addition or subtraction of heat, we are able, from Equation (15), to deduce the law connecting the tension and the pressure. For if we call v' and v'_0 the volume at any instant and the initial volume of the permanent gases, we have from (15)

$$p = p_0\left(\frac{v'_0}{v'}\right)^{\frac{C_p}{C_v}} \quad . \quad . \quad . \quad . \quad (17)$$

but if a be the ratio which the volume of the non-gaseous products at the moment of explosion bears to that of the unexploded powder, we have

$$v'_0 = v_0(1-a), \quad v' = v - av_0 \quad . \quad . \quad . \quad (18)$$

and Equation (17) becomes

$$p = p_0\left(\frac{v_0(1-a)}{v - av_0}\right)^{\frac{C_p}{C_v}} \quad . \quad . \quad . \quad (19)$$

and this is the relation between p and v on Bunsen and Schischkoff's hypothesis.

Taking, as before, $p_0=41{\cdot}477$, $v_0=1$, and remembering that we have found the value of α to be ·6, we have

$$p = 41{\cdot}477\left(\frac{\cdot 4}{v - \cdot 6}\right)^{\frac{C_p}{C_v}} \quad . \quad . \quad . \quad (20)$$

The value of the exponent $\frac{C_p}{C_v}$ can be deduced from the data given in Table 16.

Table 16.—*Showing the percentage weights, specific heats at constant volume, and the specific heats at constant pressure of the permanent gases produced by the explosion of powder.*

Nature of gas.	Percentage weight of gas.	Specific heat at constant pressure.	Specific heat at constant volume.
Sulphuretted hydrogen .	·0262	·2432	·1840
Carbonic oxide . . .	·1036	·2450	·1736
Carbonic anhydride . .	·6089	·2169	·1720
Marsh-gas	·0012	·5929	·4680
Hydrogen	·0023	3·4090	2·4110
Nitrogen	·2579	·2438	·1727

From the data in this table the value of C_p is found to be $=$ ·23528, of $C_v=$·1782, and that of the fraction $\frac{C_p}{C_v}=1{\cdot}3203$; and Equation (20) becomes

$$p = 41{\cdot}477\left(\frac{\cdot 4}{v - \cdot 6}\right)^{1{\cdot}3203} \quad . \quad . \quad . \quad . \quad (21)$$

The results of (16) and (21) are given in Table 17; and in the same table are given the values of p, both as deduced from actual experiment in the bore of the 10-inch and 11-inch guns (see Plate XVIII., p. 230), and also as deduced from our experiments in a close vessel. The results of the experiments upon the tension of different densities in a close vessel represent of course the elastic force which would exist were the gas allowed to expand in a vessel impervious to heat, without production of work.

TABLE 17.—*Showing in terms of the density* (1) *the tension actually found to exist in the bores of guns;* (2) *the tension which would exist were the gases suffered to expand without production of work;* (3) *the tension calculated upon De Saint-Robert's hypothesis;* (4) *the tension calculated on Bunsen and Schischkoff's hypothesis.*

Mean density of products of combustion.	Tension observed in bore of 18-ton gun (pebble-powder).		Tension observed where the gases expand without production of work.		Tension calculated upon Count De St.-Robert's hypothesis.		Tension calculated upon Bunsen and Schischkoff's hypothesis.	
	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.
1·00	...	...	41·48	6320	41·48	6320	41·48	6320
·90	20·35	3101	32·46	4946	35·75	5448	30·00	4572
·80	17·01	2590	25·52	3889	30·14	4593	21·85	3330
·70	14·03	2133	20·02	3051	25·08	3822	15·85	2416
·60	11·33	1722	15·55	2370	20·18	3076	11·62	1771
·50	8·87	1352	11·85	1806	15·61	2378	7·93	1209
·40	6·65	1019	8·73	1330	11·40	1736	5·30	808
·30	4·67	722	6·07	925	7·60	1157	3·28	500
·20	2·93	459	3·77	574	4·29	653	1·75	267
·10	...	...	1·77	270	1·61	246	·64	98

The graphical representation of this table is given in Plate XIX. (p. 230); and by examination either of the table or of the curves, it is obvious that neither Formula (16) nor (21) gives results which can be taken as at all representing the truth. The values of the elastic force, calculated on the assumption that the whole of the products of combustion are in the gaseous state, and that the effect on the projectile is produced by such expansion, are largely in excess of the pressures observed in the gun, and very greatly in excess even of the pressures observed when the gases were expanded without production of work. On the other hand, the pressures calculated on the assumption that the work is caused by the expansion of the permanent gases *alone*, without addition or subtraction of heat, are considerably in defect of those actually observed, and this too, although no allowance is made for the absorption of heat by the gun.

At an early stage in our researches, when we found, contrary to our expectation, that the elastic pressures deduced from experiments in close vessels did not differ greatly (where the powder might be considered entirely consumed, or nearly so) from those deduced from experiments in the bores of guns themselves, we came to the conclusion that this departure from our expectation was probably due to the heat stored up in the liquid residue. In fact, instead of the expansion of the permanent gases taking place without addition of

heat, the residue, in the finely divided state in which it must be on the ignition of the charge, may be considered a source of heat of the most perfect character, and available for compensating the cooling effect due to the expansion of the gases on production of work.

The question, then, that we now have to consider is—What will be the conditions of expansion of the permanent gases when dilating in the bore of a gun and drawing heat, during their expansion, from the non-gaseous portions in a very finely divided state?

To solve this question we must have recourse to certain well-known principles of thermodynamics.

Let $d\mathrm{H}$ be the quantity of heat added to, or drawn from, the non-gaseous portion of the charge by the permanent gases, while the latter pass from the volume v' and temperature t to the volume $v'+dv'$ and temperature $t+dt$, we then have *

$$d\mathrm{H} = t\,.\,d\phi \qquad (22)$$

ϕ being Rankine's thermodynamic function.

But if λ be the specific heat of the non-gaseous portion of the charge, and if β be the ratio between the weights of the gaseous and non-gaseous portions of the charge, and if we assume further, as we can do without material error, that λ is constant, we shall have

$$d\mathrm{H} = -\beta\lambda dt \qquad (23)$$

$$\therefore \quad d\phi = -\beta\lambda\frac{dt}{t} \qquad (24)$$

and by integration

$$\phi - \phi_0 = \log_e\left(\frac{t}{t_0}\right)^{-\beta\lambda} \qquad (25)$$

But the value of $\phi-\phi_0$ for permanent gases is well known, being readily deduced from the general expression for the thermodynamic function.

This expression being †

$$\phi = \mathrm{C}\log_e t + \frac{1}{\mathrm{J}}\cdot\int\frac{dp}{dt}\,.\,dv' \qquad (26)$$

(J being Joule's equivalent), and $\frac{dp}{dt}$ being readily obtained from the equation of elasticity and dilatability of perfect gases,

$$pv' = \mathrm{R}t$$

* Rankine, *Steam Engine*, p. 310. De Saint-Robert, *loc. cit.*, p. 68.
† Rankine, *loc. cit.*, p. 311. De Saint-Robert, *loc. cit.*, p. 72.

we deduce from (26), by integration,

$$\phi - \phi_0 = \log_e \left(\frac{t}{t_0}\right)^{C_v} \cdot \left(\frac{v'}{v'_0}\right)^{\frac{R}{J}}$$

$$= \log_e \left(\frac{t}{t_0}\right)^{C_v} \cdot \left(\frac{v'}{v'_0}\right)^{C_p - C_v} \quad . \quad . \quad (27)$$

since * $\frac{R}{J} = C_p - C_v$.

Hence, equating (25) and (27),

$$1 = \left(\frac{t}{t_0}\right)^{C_v + \beta\lambda} \cdot \left(\frac{v'}{v'_0}\right)^{C_p - C_v}$$

Therefore

$$\frac{t}{t_0} = \left(\frac{v'_0}{v'}\right)^{\frac{C_p - C_v}{C_v + \beta\lambda}} \quad . \quad . \quad . \quad . \quad (28)$$

and

$$\frac{p}{p_0} = \left(\frac{v'_0}{v'}\right)^{\frac{C_p + \beta\lambda}{C_v + \beta\lambda}} \quad . \quad . \quad . \quad . \quad (29)$$

or, since $v'_0 = v_0(1-\alpha)$, $v' = v - \alpha v_0$,

$$\frac{p}{p_0} = \left\{\frac{v_0(1-\alpha)}{v - \alpha v_0}\right\}^{\frac{C_p + \beta\lambda}{C_v + \beta\lambda}} \quad . \quad . \quad . \quad (30)$$

and Equation (30) gives the true relation connecting p and v when the gaseous products expand in the bore of a gun with production of work.

The values of the constants in this equation we have already determined; they are as follow:—

$$C_v = \cdot 1782, \quad C_p = \cdot 2353, \quad p_0 = 41 \cdot 477, \quad \lambda = \cdot 4090, \quad \beta = 1 \cdot 3148.$$

The results of Equation (30) are given in Table 18, p. 200; and, as before, for comparison we give similar values of p both as derived from experiments with heavy ordnance and on the supposition of expansion without performance of work.

The results of Table 18 are graphically represented in Plate XX. (p. 230); and on the axis of abscissæ are figured, for convenience, both the density of the products and the volume they occupy.

* Rankine, *loc. cit.*, p. 318. Clausius, *loc. cit.*, p. 39. De Saint-Robert, *loc. cit.*, p. 93.

TABLE 18.—*Giving, in terms of the density, the tensions actually found to exist in the bores of guns with pebble and R. L. G. powders; giving, further,* (1) *the tensions calculated from Equation* (30); (2) *the tension which would exist were the gases suffered to expand without production of work.*

Mean density of products of combustion.	Tension observed in bores of guns. Pebble-powder.		Tension observed in bores of guns. R. L. G. powder.		Tension calculated from Formula (30).		Tension observed when the gases expand without production of work.	
	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.
1·00	...	...	...	...	41·48	6316	41·48	6316
·95	...	...	...	...	36·30	5528	36·65	5581
·90	20·35	3099	27·33	4162	31·84	4848	32·46	4943
·85	18·63	2837	24·63	3751	27·95	4256	28·78	4383
·80	17·01	2590	22·01	3352	24·56	3740	25·53	3888
·75	15·48	2357	19·50	2969	21·56	3283	22·63	3446
·70	14·03	2136	17·16	2613	18·89	2877	20·02	3049
·65	12·65	1926	15·05	2292	16·51	2514	17·68	2692
·60	11·33	1725	13·21	2011	14·38	2190	15·55	2368
·55	10·07	1533	11·61	1768	12·46	1897	13·62	2074
·50	8·87	1351	10·18	1550	10·72	1632	11·85	1804
·45	7·73	1177	8·87	1351	9·15	1393	10·23	1558
·40	6·65	1013	7·65	1165	7·71	1174	8·73	1329
·35	5·63	857	6·49	988	6·40	975	7·35	1119
·30	4·67	711	5·39	821	5·21	793	6·07	924
·25	3·77	574	4·34	661	4·11	626	4·88	743
·20	2·93	446	3·33	507	3·11	474	3·77	574
·15	2·15	327	2·35	358	2·20	335	2·73	416
·10	..	...	...	...	1·37	209	1·76	268

The curve marked A represents the tensions deduced (with a slight correction for loss of heat) from actual observation in a close vessel, and may, as we have already said, be taken to represent the pressures that would exist were the products of combustion allowed to expand in a vessel impervious to heat and without production of work.

The curve marked B, derived from Equation (30), denotes the tensions that would exist in the bore of a gun, if we suppose the powder, of a gravimetric density = 1 and filling entirely the chamber, to be completely consumed before the projectile is moved from its place, and to expand in a gun impervious to heat. By comparison with the curve A will be seen the difference in tension arising from the loss of heat due to the work expended. The great importance of the heat contained in the non-gaseous portion of the charge is rendered apparent by comparison of curve B with curve 4, Plate XIX. (p. 230), or Table 17, where, on Bunsen and Schischkoff's hypothesis, the permanent gases are supposed to expand without deriving any heat from the non-gaseous portion of the charge.

The area comprised between curve B and the axis of abscissæ represents the maximum work that it is possible to obtain from powder.

Curve C represents the mean results obtained with R. L. G. powder from the 8-inch and 10-inch guns, and curve D represents the mean results obtained with pebble-powder from the 10-inch and 11-inch guns.

It is interesting to study the differences exhibited by these curves B, C, and D. The curve C, representing the pressures obtained with R. L. G., denotes tensions not far removed from the theoretic curve, while the densities are still very high; before the volume is much increased, the two curves slide into one another and become almost coincident.

The curve D, on the other hand, is at first very considerably below both the R. L. G. and the theoretic curve. It is still considerably lower even when the R. L. G. curve is practically coincident with the theoretic curve, and it retains a measurable though slight inferiority of pressure even up to the muzzle of the gun.

These differences are without doubt due to the fact that with the R. L. G. powder, at least under ordinary circumstances, the whole or a large proportion of the charge is consumed before the projectile is greatly removed from the seat of the shot. With the slower-burning pebble-powder, on the other hand, a considerable quantity of powder remains unconsumed until the projectile approaches the muzzle; and the curve indicates in a very striking way the gradual consumption of the powder, and the portion of the bore in which the slow-burning powder may be considered practically burned.

It might perhaps be expected that the difference between the theoretic curve B and the observed curves C and D near the muzzle would be greater than is shown, since the curve B has been obtained on the supposition that the expansion has taken place in a vessel impervious to heat.

We have pointed out, however, that although in muskets and small arms the loss of heat arising from communication to the bore is very considerable, it is comparatively unimportant in very large guns. In our calculations also we have taken λ, the specific heat of the non-gaseous portion of the charge, at its mean value. It should, however, be taken at a higher value, since the specific heat must increase rapidly with the temperature; and this difference no doubt more than compensates for the loss of heat to which we have referred as not being taken into account.

Our hypothesis as to a portion of the charge remaining unconsumed until the projectile approaches the muzzle, is confirmed by the well-known fact that in short guns, or where powder of high density or very large size is employed, considerable quantities sometimes escape combustion altogether.

The appearance of pellet or pebble powder which has been ignited and afterwards extinguished in passing through the atmosphere, is well known to artillerists.

The general appearance (and in this appearance there is wonderful uniformity) is represented in Plate XI., Fig. 5 (p. 230), and gives the idea of the combustion having proceeded from centres of ignition.

If we imagine a grain, or rather (taking into account the size of the grains of the present day) a pebble, of powder arriving unconsumed at a point a little in advance of that of maximum pressure, it is not difficult to conceive that such pebble will traverse the rest of the bore without being entirely consumed, when the great influence of diminished pressure, combined with the shortness of time due to the increasing velocity of the projectile, is considered.

Thus, by reference to Table 10, it will be found that the time taken by the projectile to describe the first foot (·305 metre) of motion is about ·005 second, while the time taken to describe the remaining length of the bore, 7·25 feet (2·21 metres), is only about ·011 second.

The mean powder-pressure over the first foot, again, is about 15 tons per inch (2300 atmospheres), and over the remainder of the bore is only 5·25 tons (800 atmospheres).

(*w*) TEMPERATURE OF PRODUCTS OF COMBUSTION IN BORES OF GUNS.

The temperature in the bore of the gun during the expansion of the products is given by Equation (28), or, restoring the values of v' and v'_0,

$$t = t_0\left\{\frac{v_0(1-\alpha)}{v-\alpha v_0}\right\}^{\frac{c_p-c_v}{c_v+\beta\lambda}} \quad . \quad . \quad . \qquad (31)$$

The temperatures calculated from this formula are given in Table 19. It is hardly necessary to point out that the values given in this table are only strictly accurate when the charge is ignited before the projectile is sensibly moved; but in practice the correction due to this cause will not be great.

TABLE 19.—*Giving the temperature in degrees Centigrade, and in terms of the density, of the products when expanded, with production of work, in the bore of a gun supposed impervious to heat.*

Mean density of products of combustion.	Number of volumes of expansion.	Temperature. Degrees Centigrade.	Mean density of products of combustion.	Number of volumes of expansion.	Temperature. Degrees Centigrade.
1·00	1·0000	° 2231	·50	2·0000	° 2019
·95	1·0526	2209	·45	2·2222	1996
·90	1·1111	2188	·40	2·5000	1971
·85	1·1765	2167	·35	2·8571	1943
·80	1·2500	2146	·30	3·3333	1914
·75	1·3333	2126	·25	4·0000	1881
·70	1·4286	2105	·20	5·0000	1843
·65	1·5385	2084	·15	6·6667	1796
·60	1·6667	2063	·10	10·0000	1734
·55	1·8182	2041	·05	20·0000	1637

(*x*) WORK EFFECTED BY GUNPOWDER.

The theoretic work which a charge of gunpowder is capable of effecting during the expansion to any volume v is, as we have said, represented by the area between the curve B, Plate XX. (p. 230), the ordinates corresponding to v and v_0, and the axis of abscissæ. In mathematical language, it is expressed by the definite integral

$$\int_{v_0}^{v} p \, . \, dv \quad . \quad . \quad . \quad . \quad (32)$$

Replacing in this equation the value of p derived from Equation (30) we have for the work done by the powder in expanding from v_0 to v,

$$W = p_0 \int_{v_0}^{v} \left\{ \frac{v_0(1-a)}{v - av_0} \right\}^{\frac{C_p+\beta\lambda}{C_v+\beta\lambda}} . \, dv \quad . \quad . \quad . \quad . \quad (33)$$

$$= \frac{p_0 v_0 (1-a)(C_v+\beta\lambda)}{C_p - C_v} \left\{ 1 - \left(\frac{v_0(1-a)}{v-av_0} \right)^{\frac{C_p-C_v}{C_v+\beta\lambda}} \right\} \quad . \quad (34)$$

The values of all the constants in this equation have already been given; but for our present purpose it is convenient to determine the work which 1 grm. of powder is capable of performing for different degrees of expansion. Assuming, then, that a gramme of powder is of the gravimetric density of unity (that is, that it occupies a volume of 1 c.c.), we have $v_0=1$; and expressing the initial pressures 41·5 tons (6320 atmospheres) in grammes per square centimetre, we have $p_0=6{,}532{,}450$ grms. per square centimetre.

We have calculated W from (34) from various values of v up to and inclusive of $v=20$. The results are embodied in the following

table, and are expressed both in kilogrammetres per kilogramme and foot-tons per lb. of powder.

TABLE 20.—*Giving the total work that gunpowder is capable of performing in the bore of a gun, in kilogrammetres per kilogramme and foot-tons per lb. of powder burned, in terms of the density of the products of explosion.*

		Total work that the gunpowder is capable of realising.	
Density of products of combustion.	Number of volumes of expansion.	Per kilogramme burned in kilogrammetres.	Per lb. burned in foot-tons.
·95	1·0526	3210·8	4·70
·90	1·1111	6339·6	9·29
·85	1·1768	9412·8	13·79
·80	1·2500	12443·3	18·23
·75	1·3333	15460·8	22·65
·70	1·4286	18488·1	27·08
·65	1·5385	21544·9	31·56
·60	1·6667	24650·8	36·11
·55	1·8182	27841·9	40·78
·50	2·0000	31153·7	45·62
·45	2·2222	34614·0	50·70
·40	2·5000	38290·0	56·08
·35	2·8571	42234·7	61·86
·30	3·3333	46565·9	68·21
·25	4·0000	51414·8	75·31
·20	5·0000	57031·7	83·53
·17	5·8824	60952·1	89·35
·16	6·2500	62368·1	91·45
·15	6·6667	63884·4	93·64
·14	7·1429	65470·1	95·94
·13	7·6923	67138·4	98·39
·12	8·3333	68940·1	101·00
·11	9·0909	70855·4	103·82
·10	10·0000	72903·7	106·87
·9	11·1111	75214·5	110·18
·8	12·5000	77679·9	113·81
·7	14·2857	80462·1	117·85
·6	16·6667	83582·1	122·42
·5	20·0000	87244·4	127·79

The results embodied in this table are of very considerable importance. They enable us to say by simple inspection what is the maximum work that can be obtained from powder such as is employed by the British Government in any given length of gun. To make use of the table, we have only to find the volume occupied by the charge (gravimetric density$=1$) and the number of times this volume is contained in the bore of the gun. The maximum work*

* It is hardly necessary to point out that the velocity of the projectile at any point of the bore is directly deducible from Equation (34). For the velocity being connected with the work by the equation

$$\text{velocity} = \sqrt{\frac{2g}{w} . \mathrm{W}}$$

per kilogramme or pound which the powder is capable of performing during the given expansion, is then taken out from the table; and this work being multiplied by the number of kilogrammes or pounds in the charge, gives the total maximum work. Thus, for example, in an 18-ton 10-inch gun, a charge of 70 lbs. (31·75 kilos.) pebble-powder is fired, and we wish to know what is the maximum work that the charge is capable of performing. We readily find that the length of the gun is such that $v=5{\cdot}867$ vols.; and from the table we find that 89·4 foot-tons or 61,000 kilogrammetres is the maximum work per lb. or per kilog.; multiplying by the number of pounds or kilos., we find that 6258 foot-tons or 1,936,750 kilogrammetres is the maximum work which the whole charge is capable of performing.

As a matter of course, this maximum effect is only approximated to, not attained; and for actual use it would be necessary to multiply the work so calculated by a factor dependent upon the nature of the powder, the mode of firing it, the weight of the shot, etc.; but in service-powders fired under the same circumstances, the factor will not vary much. In the experimental powders used by the Committee on Explosives, there were, it is true, very considerable differences, the work realised in the same gun varying from 56 foot-tons to 86 foot-tons per lb. of powder; but with service-powders fired under like conditions this great difference does not exist.

We have prepared at once, in illustration of the principles we have just laid down, as a test of the general correctness of our views and as likely to prove of considerable utility, a table in which we have calculated, from the data given, first, the total work realised per lb. of powder burned for every gun, charge, and description of powder in the English service; second, the maximum theoretic work per lb. of powder it would be possible to realise with each gun and charge; and third, the factor of effect with each gun and charge—that is, the percentage of the maximum effect actually realised.

w being the weight of the shot, we have only to take out, from Equation (34) or Table 20, the value of W for any given expansion, multiply it by the "factor of effect" (see p. 206) for the particular gun, charge, etc., and use in the above equation the value of W so found.

As an illustration, if it be required to determine the velocity at the muzzle of the 10-inch gun under the circumstances discussed at p. 205, the total work, as shown in the text, which the charge is capable of effecting, is 6258 foot-tons; multiplying this by the factor for the gunpowder and weight of shot, we have $W=4880$ foot-tons; substituting this value of W in the above equation, we obtain $v=1532$ feet, or nearly identical with the observed velocity.

TABLE 21.—*Giving, with the data necessary for calculation, the work per lb. of powder realised, the total maximum theoretic work, and the factor of effect for every gun and charge in the British Service.*

Nature of gun.	Bore.		Charge.			Projectile.		Gas.		Energy of powder.			
	Dia-meter.	Length.	Nature.	Weight.		Weight.	Velocity.	Total volumes in bore.	Final density.	Total.	Realised per lb. of powder.	Calculated maximum.	Percentage realised.
	Inches.	Calibres.		Lbs.	oz.	Lbs.	Feet per sec.			Foot-tons.	Foot-tons.	Foot-tons.	
38 tons	12	16·5	P.	110	0	700	1430	7·342	·1362	9932	90·3	97·0	93·1
35 tons	12	13·5	P.	110	0	700	1300	6·007	·1665	8209	74·6	90·2	82·7
25 tons	12	12·0	P.	85	0	600	1300	6·910	·1447	7036	82·8	94·9	87·3
			P.	85	0	495	1358	6·910	·1447	6334	74·5	94·9	78·6
			P.	55	0	495	1142	10·679	·0936	4479	81·4	108·9	74·8
			R. L. G.	67	0	600	1180	8·765	·1141	5797	86·4	102·8	84·1
			R. L. G.	67	0	495	1271	8·765	·1141	5549	82·8	102·8	80·6
			R. L. G.	50	0	495	1140	11·750	·0851	4464	89·3	111·8	80·0
25 tons	11	13·2	P.	85	0	535	1315	5·585	·1708	6419	75·5	89·2	84·7
			P.	85	0	535	1315	5·855	·1700	6419	75·5	89·2	84·7
			R. L. G.	70	0	535	1217	7·109	·1407	5498	78·6	95·8	82·1
			R. L. G.	70	0	535	1217	7·109	·1407	5498	78·6	95·8	82·1
18 tons	10	14·5	P.	70	0	400	1364	5·867	·1704	5164	73·8	89·4	82·6
			P.	70	0	400	1340	5·867	·1704	4984	71·2	89·4	79·7
			P.	44	0	400	1125	9·334	·1071	3513	79·8	104·7	76·3
			R. L. G.	60	0	400	1298	6·844	·1461	4676	77·9	94·5	82·4
			R. L. G.	40	0	400	1117	10·269	·0974	3463	86·6	107·9	80·3
12½ tons	9	13·9	P.	50	0	250	1420	5·742	·1742	3498	70·0	88·6	79·1
			P.	50	0	250	1420	5·742	·1742	3498	70·0	88·6	79·1
			R. L. G.	43	0	250	1336	6·683	·1496	3096	72·0	93·6	77·1
			R. L. G.	43	0	250	1336	6·683	·1496	3096	72·0	93·6	77·1
			R. L. G.	30	0	250	1192	9·566	·1045	2465	82·2	105·2	78·2
9 tons	8	14·8	P.	35	0	180	1413	6·136	·1630	2493	71·3	90·9	78·4
			P.	35	0	180	1413	6·136	·1630	2493	71·3	90·9	78·4
			R. L. G.	30	0	180	1330	7·154	·1398	2209	73·7	96·0	76·8
			R. L. G.	30	0	180	1330	7·154	·1398	2209	73·7	96·0	76·8
			R. L. G.	20	0	180	1163	10·724	·0932	1689	84·5	109·1	77·6

7 tons	7	18·0	P.	30	0	115	1561	5·827	·1716	1945	64·8	89·0	72·9
			P.	30	0	115	1561	5·827	·1716	1945	64·8	89·0	72·9
			R. L. G.	22	0	115	1458	7·948	·1258	1696	77·1	99·4	77·6
			R. L. G.	22	0	115	1458	7·948	·1258	1696	71·1	94·4	77·6
			R. L. G.	14	0	115	1258	12·495	·0800	1263	90·2	113·3	79·7
6½ tons	7	15·9	P.	30	0	115	1525	5·148	·1943	1856	61·9	84·6	73·2
			P.	30	0	115	1525	5·148	·1943	1856	61·9	84·6	73·2
			R. L. G.	22	0	115	1430	7·021	·1424	1632	74·2	95·5	77·7
			R. L. G.	22	0	115	1430	7·021	·1424	1632	74·2	95·5	77·7
			R. L. G.	14	0	115	1230	11·039	·0906	1207	86·2	110·0	78·4
80-pr. of 101 cwt. . .	6·3	18·0	L. G.	10	0	80	1240	12·748	·0784	835·5	85·4	114·1	74·9
64-pr. of 64 cwt. wrt. iron	6·3	15·5	R. L. G.	8	0	64	1252	13·715	·0729	696·1	87·0	116·0	75·1
			L. G.	8	0	64	1229	13·715	·0729	670·8	83·8	116·0	72·3
64-pr. of 58 cwt. . .	6·3	17·2	R. L. G.	8	0	64	1245	15·234	·0656	688·3	86·0	118·7	72·5
64-pr. of 71 cwt. . .	6·3	16·4	R. L. G.	8	0	64	1230	14·518	·0689	671·9	84·0	117·3	71·6
40-pr. of 35 cwt. . .	4·75	18·0	R. L. G.	8	0	40	1357	6·830	·1464	511·1	63·9	94·6	67·6
			R. L. G.	7	0	40	1336	7·805	·1281	495·4	70·8	99·1	71·5
			R. L. G.	6	0	40	1305	9·105	·1098	472·7	78·8	103·8	76·0
25-pr. of 21 cwt. . .	4·0	18·0	R. L. G.	5	0	25	1355	6·518	·1534	318·5	63·7	92·8	68·7
			R. L. G.	4	0	25	1320	7·244	·1380	302·3	67·2	96·4	69·8
			R. L. G.	4	0	25	1278	8·151	·1227	283·3	70·8	100·4	70·5
16-pr. of 12 cwt. . .	3·6	19·0	R. L. G.	3	0	16	1352	8·365	·1195	202·9	67·6	101·0	67·9
			R. L. G.	2	8	16	1273	10·043	·0996	179·9	72·0	106·8	67·5
			R. L. G.	2	0	16	1167	12·541	·0797	151·2	75·6	113·4	66·6
9-pr. of 8 cwt. . . .	3·0	21·3	R. L. G.	1	12	9	1381	9·320	·1073	119·1	68·0	104·6	65·1
			R. L. G.	1	8	9	1325	10·865	·0920	109·6	73·1	109·5	66·9
			R. L. G.	1	4	9	1203	13·026	·0768	90·38	72·3	114·5	63·2
9-pr. of 6 cwt. . . .	3·0	17·5	R. L. G.	1	12	9	1262	7·649	·1307	99·46	56·8	98·1	57·9
			R. L. G.	1	8	9	1234	8·918	·1121	95·10	63·4	103·5	61·3
7-pr. of 220 lb. (bronze) .	3·0	11·3	F. G.	0	12	7·25	955	11·538	·0867	45·88	61·2	111·0	55·2
			F. G.	0	10	7·25	854	13·873	·0721	36·69	58·7	116·0	50·6
7-pr. of 150 lb. (steel) .	3·0	8·0	F. G.	0	6	7·25	673	16·346	·0612	22·79	60·8	121·0	50·5
7-inch B.L. of 82 cwt. .	7·0	14·2	R. L. G.	10	0	110	1013	13·794	·0725	783·2	78·3	116·0	67·5
			R. L. G.	11	0	90	1165	12·541	·0797	847·6	77·1	113·0	68·0
64-pr. B.L. of 61 cwt. .	6·4	10·9	R. L. G.	9	0	64	1200	8·982	·1113	639·5	71·1	103·5	68·8
40-pr. B.L. of 35 cwt. .	4·75	22·4	R. L. G.	5	0	41	1180	13·590	·0736	396·1	79·2	115·6	68·6
20-pr. B.L. of 16 cwt. L.S.	3·75	22·4	R. L. G.	2	8	21	1130	13·377	·0748	186·1	74·4	115·3	64·5
20-pr. B.L. of 13 cwt. S.S.	3·75	14·5	R. L. G.	2	8	21	1000	8·672	·1153	145·7	58·3	102·4	57·0
12-pr. B.L. of 8 cwt. .	3·0	20·5	R. L. G.	1	8	11·75	1150	10·457	·0956	107·8	71·9	108·0	67·9
9-pr. B.L. of 6 cwt. . .	3·0	17·7	R. L. G.	1	2	9·25	1057	12·019	·0832	71·71	63·7	112·1	56·9
6-pr. B.L. of 3 cwt. . .	2·5	21·2	R. L. G.	0	12	6·6	1046	12·500	·8000	50·11	66·8	113·4	59·0

If the factors of effect be examined, it will be observed how, in spite of the use of slow-burning and therefore uneconomical powders in the large guns, the percentages realised gradually increase as we pass from the smallest to the largest gun in our table—the highest factor being 93 per cent. in the case of the 38-ton gun, the lowest being 50·5 per cent. in the case of the little Abyssinian gun.

This difference in effect is of course in some measure due to the communication of heat to the bore of the gun, to which we have so frequently referred.

(y) DETERMINATION OF TOTAL THEORETIC WORK OF POWDER WHEN INDEFINITELY EXPANDED.

To determine the total work which powder is capable of performing if allowed to expand indefinitely, the integral in Equation (33) must be taken between ∞ and v_0. If so taken, we have

$$\text{Total work} = \frac{p_0 v_0 (1-\alpha)(C_v + \beta\lambda)}{C_p - C_v} \quad . \quad . \quad . \quad (35)$$

$$= 332{,}128$$

gramme-metres per gramme of powder (486 foot-tons per lb. of powder).

Bunsen and Schischkoff's estimate of the work which powder is capable of performing on a projectile, if indefinitely expanded, we have already given; but their estimate (being only the fifth part of that at which we have arrived) is altogether erroneous, as these eminent chemists appear to have overlooked the important part which the non-gaseous portion of the charge plays in expansion.

It is interesting to compare the above work of gunpowder with the total theoretic work of 1 grm. of coal, which is about 3,400,000 grm.-units. The work stored up in 1 grm. of coal is therefore more than ten times as great as that stored up in 1 grm. of powder.

The powder, it is true, contains all the oxygen necessary for its own combustion, while the coal draws nearly 3 grms. of oxygen from the air. Even allowing, however, for this, there is a considerable inferiority in the work done by gunpowder, which is doubtless in part due to the fact that the coal finds its oxygen already in the form of gas, while a considerable amount of work is expended by the gunpowder in placing its oxygen in a similar condition.

In an economic point of view also the oxygen stored up in the gunpowder is of no importance, as that consumed by coal costs nothing, while the oxygen in the powder is in a most expensive form. The fact is perhaps worth noting as demonstrating the impractica-

bility of making economic engines deriving their motive power from the force of gunpowder.

(z) SUMMARY OF RESULTS.

It only now remains to summarise the principal results at which we have arrived in the course of our researches; (*a*) when gunpowder is fired in a space entirely confined; (*b*) when it is suffered to expand in the bore of a gun.

(*a*) The results when powder is fired in a close space are as follow, and for convenience are computed upon 1 grm. of powder occupying a volume of 1 c.c.:—

1. On explosion, the products of combustion consist of about 57 per cent. by weight of matter, which ultimately assumes the solid form, and 43 per cent. by weight of permanent gases.

2. At the moment of explosion, the fluid products of combustion, doubtless in a very finely divided state, occupy a volume of about ·6 c.c.

3. At the same instant the permanent gases occupy a volume of 4 c.c., so that both the fluid and gaseous matter are of approximately the same specific gravity.

4. The permanent gases generated by the explosion of a gramme of powder are such that, at 0° Cent. and 760 mm. barometric pressure, they occupy about 280 c.c., and therefore about 280 times the volume of the original powder.

5. The chemical constituents of the solid products are exhibited in Tables 3 and 6.

6. The composition of the permanent gases is shown in the same tables.

7. The tension of the products of combustion, when the powder fills entirely the space in which it is fired, is about 6400 atmospheres, or about 42 tons per square inch.

8. The tension varies with the mean density of the products of combustion according to the law given in Equation (3).

9. About 705 grm.-units of heat are developed by the decomposition of 1 grm. of powder such as we have used in our experiments.

10. The temperature of explosion is about 2200° Cent. (about 4000° Fahr.).

(*b*) When powder is fired in the bore of a gun, the results at which we have arrived are as follows:—

1. The products of explosion, at all events as far as regards the

proportions of the solid and gaseous products, are the same as in the case of powder fired in a close vessel.

2. The work on the projectile is effected by the elastic force due to the permanent gases.

3. The reduction of temperature due to the expansion of the permanent gases is in a great measure compensated by the heat stored up in the liquid residue.

4. The law connecting the tension of the products of explosion with the volume they occupy is stated in Equation (30).

5. The work that gunpowder is capable of performing in expanding in a vessel impervious to heat is given by Equation (34), and the temperature during expansion is given in Equation (31).

6. The total theoretic work of gunpowder when indefinitely expanded is about 332,000 grm.-metres per gramme of powder, or 486 foot-tons per lb. of powder.

With regard to one or two other points to which we specially directed our attention in these investigations, we consider that our results warrant us in stating that:—

1. Very small-grain powder, such as F. G. and R. F. G., furnish decidedly smaller proportions of gaseous products than a large-grain powder (R. L. G.), while the latter again furnishes somewhat smaller proportions than a still larger powder (pebble), though the difference between the gaseous products of these two powders is comparatively inconsiderable.

2. The variations in the composition of the products of explosion furnished in close chambers by one and the same powder under different conditions as regards pressure, and by two powders of similar composition under the same conditions as regards pressure, are so considerable that no value whatever can be attached to any attempt to give a general chemical expression to the metamorphosis of a gunpowder of normal composition.

3. The proportions in which the several constituents of solid powder-residue are formed, are quite as much affected by slight accidental variations in the conditions which attend the explosion of one and the same powder in different experiments as by decided differences in the composition as well as in the size of grain of different powders.

4. In all but very exceptional results the solid residue furnished by the explosion of gunpowder contains, as important constituents, potassium carbonate, sulphate, hyposulphite, and sulphide, the proportion of carbonate being very much higher,

and that of sulphate very much lower, than stated by recent investigators.

ABSTRACT OF EXPERIMENTS.

In this abstract the following abbreviations are used:—

δ to represent the mean density of the products of explosion; A the area of the piston of the crusher-gauge; a the sectional area of the crushing-cylinder.

Experiment 1, April 20, 1871.—The cylinder (Fig. 2, Plate X., p. 230) having been prepared for the experiments, was calibrated and found to contain 14,000 grs. (907·20 grms.). A charge of 1400 grs. (90·72 grms.) R. L. G. powder was then placed in the cylinder and fired.

The gaseous products of combustion were collected in tubes and sealed.

On opening the cylinder the solid products of combustion were found adhering to the sides pretty uniformly, but thicker at the bottom; they had to be scraped off for collection.

δ.	A.	a.	Crush, copper cylinder.	Pressure per square inch.
·0940	·1667	·0417	·009	1·6 ton.

Experiment 2, April 4, 1871.—Fired 3500 grs. (226·80 grms.) R. L. G. powder as above, in a similar cylinder, the powder exactly filling the space in which it was confined.

The gas was retained in the cylinder for about a second, and then, owing to a want of accurate fit in the collecting-screw, made its escape with a considerable explosion, completely, so to speak, washing away every trace both of the male and female screw along the channel it cut out for itself.

On opening the cylinder but little solid residue was found, and that uniformly distributed over the surface, and about ·07 inch thick.

Its colour was of a very bright vermilion red, rapidly changing to black on the surface, and was similar in all respects to the deposit so often seen in the powder-chambers of heavy guns.

Residue collected and sealed up in a test-tube.

δ.	A.	a.	Crush, copper cylinder.	Pressure per square inch.
·915	·1667	·0833	·293	34·5 tons.

Experiment 3, April 29, 1871.—Cylinder No. 6 calibrated and found to contain 14,702 grs. (952·68 grms.). 2940 grs. R. L. G. (190·54 grms.) were fired and the gases collected within fifteen minutes after firing.

On opening the cylinder the solid products were found to be collected at the bottom, only a very thin light-coloured deposit being on the sides.

The appearance of the deposit was very different from any yet obtained, being grey on the smooth surface and very bright yellow in fracture. It was exceedingly hard and very deliquescent.

The interior surface of the cylinder appeared quite bright when the deposit was removed.

A portion of the deposit, whitish on the surface, dark grey next the cylinder, was collected and sealed in separate test-tubes.

A tin cylinder was substituted for copper, to measure the crush in this experiment.

δ.	A.	a.	Crush, tin cylinder.	Pressure per square inch.
·1973	·1667	·0833	·165	2·67 tons.

Experiment 4, May 10, 1871.—4411 grs. (285·5 grms.) of R. L. G. powder were fired in cylinder No. 7. Gases were collected, commencing seven minutes after explosion.

On opening the cylinder the solid products were found in a mass at the bottom; and the sides of the cylinder were also as noted in the last experiment.

The residue, however, was of intense hardness, and the difficulty of removing it was very great. Hardly any could be got off in lumps, but it flew off like sand before the chisel.

Copper firing-wire fused off and dropped in the form of a button.

δ.	A.	a.	Crush, copper cylinder.	Pressure per square inch.
·2963	·1677	·0833	·033	6·4 tons.

Experiment 5, June 22, 1871.—Cylinder No. 6 calibrated and found to contain 15,859 grs. P. powder. Fired 1586 grs. (102·77 grms.) P.; but, owing to the low pressure, the cylinder did not become closed up very tightly, and most of the gas slowly escaped.

Solid products at the bottom, and easily removed. Colour light grey on surface, dark grey next steel, shading into light grey near the surface.

δ.	A.	a.	Crush, tin cylinder.	Pressure per square inch.
·1064	·1667	·0833	·042	1·39 ton.

Experiment 6, June 28, 1871.—Fired 1586 grs. (102·77 grms.) pebble in same cylinder (No. 6) as that used in the last experiment.

Nearly all the gas escaped from the same cause (defect of pressure). Products of combustion not collected.

δ.	A.	a.	Crush, tin cylinder.	Pressure in tons.
·1064	·1667	·0833	·032	1·26

Experiment 7, June 28, 1871.—Fired 3150 grs. (204·12 grms.) pebble-powder in cylinder No. 6. Gas collected immediately. Solid products at bottom as usual, and tolerably easily detached. Colour whitish grey on the smooth surface, almost black, next steel. Fracture yellowish green with splotches of grey.

δ.	A.	a.	Crush, tin cylinder.	Pressure in tons.
·2114	·1667	·0833	·188	2·93

Experiment 8, June 29, 1871.—Fired 1586 grs. (102·77 grms.) pebble-powder in cylinder No. 6. There was a slight escape of gas at first, but the plug soon tightened. Gas collected and sealed immediately.

On opening the cylinder, the deposit was found principally at the bottom. It adhered very firmly, and was removed with great difficulty.

The colour of the smooth surface was light grey and green, buff in one or two places. Fracture yellowish green.

The portions of the residue that could not be removed with a chisel were dissolved out.

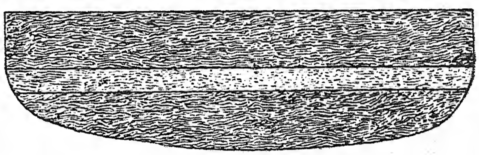
The firing copper wires ·07 in diameter were melted and had formed a button, having, however, rather long stumps.

δ.	A.	a.	Crush, tin.	Pressure in tons.
·1064	·1667	·0833	·033	1·28

Experiment 9, June 29, 1871.—Fired 4725 grs. (306·18 grms.) pebble in cylinder No. 4.

On firing there was a slight escape of gas past the crusher-gauge.

The gases were collected within five minutes of the explosion; and after the tubes were sealed a rough measurement was made of the remaining quantity of gas, which amounted to 59,000 c.c.



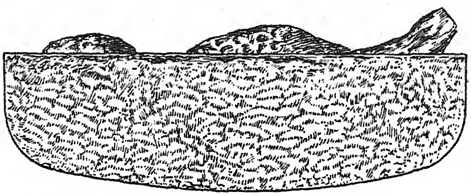
The residue was very easily detached from the cylinder. It was darker grey on the surface than in the last experiment. The fracture was a deep olive-green with a stratum of light grey in the middle, thus (see figure).

The deposit was all on the bottom, excepting a very thin coating on the sides. Firing-wires fused level with the plug.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·3171	·1667	·0833	·018	4·90

Experiment 10, July 5, 1871.—Fired 6344 grs. (411·09 grms.) P. powder in cylinder No. 6. Most of the gas escaped before enough could be collected.

Residue was found, when the cylinder was opened at the bottom, not in the usual hard compact mass, but much looser in texture. On the surface there were three large spongy projections, presenting an appearance as if the surface had been broken by the escape of occluded gas, thus (see figure).



Colour of surface grey in parts, also light yellow shading into dark yellow. Colour of fracture grey, shading off into dirty yellow and occasionally into gamboge. Powerful odour of sulphuretted hydrogen.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·4258	·1667	·0833	·054	8·4

Experiment 11, July 5, 1871.—Fired 5881 grs. (381·09 grms.) R. L. G. in cylinder No. 4. Some little escape of gas past crusher-plug. Residue very hard and adhering strongly to the side; a portion obtained in solid lumps. Colour grey on surface, black next steel. Fracture olive-green.

A good deal of the deposit was chiselled off in the form of fine dust, and this, when it had lain for a minute or two, heated very much, say to about 80° or 90° Cent., agglomerating into loose lumps and changing from a light greenish-grey colour to a bright yellow. A portion of this last deposit was collected in a separate bottle.

When the crusher-gauge was taken out, the plug at the end was found to be broken right through transversely.

The fracture was perfectly clean and bright; it was therefore

concluded that it must have broken after the great heat had subsided.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·3947	·1667	·0833	·051	8·10

Experiment 12, July 8, 1871.—Fired 6344 grs. (411·09 grms.) P. powder in cylinder No. 6. A good deal of leakage past the crusher-plug. Gas collected. Residue very hard, but it split off tolerably easily. The colour was grey throughout; fracture much the colour and appearance of slate. The difference in physical appearance between this residue and that in the last experiment was very great, the colour of the fine dust being grey, while in the last experiment it was a light yellow.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·4258	·1667	·0833	·063	9·1

Experiment 13, July 12, 1871.—Fired 7351 grs. (476·34 grms.) R. L. G. in cylinder No. 6. The products cut away the screw of the pressure-gauge and escaped.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·4934	·1667	·0833	·091	11·5

Experiment 14, July 12, 1871.—Fired 7930 grs. (513·86 grms.) P. in cylinder No. 4. Gas and residue collected as usual. Cylinder tight.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·5322	·1667	·0833	·100	12·2

Experiment 15, July 22, 1872.—Fired, in cylinder No. 6, 1586 grs. (102·77 grms.) of F. G. Cylinder perfectly tight. Gas and residue collected.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·1064	·1667	·0467	·003	1·66

Experiment 16, July 22, 1872.—Experiment 15 repeated with tin cylinder.

δ.	A.	α.	Crush, tin.	Pressure in tons.
·1064	·1667	·0467	·148	1·25

Experiment 17, July 24, 1872.—Fired, in cylinder No. 6, 3172 grs. (205·55 grms.) F. G. Collected gas and residue. Residue very

hard, but not so dark in colour as that in Experiment No. 16. Surface dark grey, but of a lighter colour when fractured. A very thin coating on the sides of the cylinder.

Small bright yellow crystals pretty uniformly distributed through the residue.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·2129	·1667	·0417	·0475	3·70

Second experiment.

·2129	·1667	·0417	·0435	3·58

Experiment 18.—Fired 4758 grs. (308·32 grms.) F. G. in cylinder No. 6. Cylinder perfectly tight. Collected gas and residue.

On opening the cylinder the residue was found all collected at the bottom; and it had evidently run down the sides in a very fluid state, the deposit on the side being very thin. Colour on surface dark grey. Fracture more uniform than usual, there being no patches of yellow and but few of a lighter colour.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·3193	·1667	·0467	·132	6·75

Experiment 19, August 26, 1872.—Fired, in cylinder No. 6, 6344 grs. (411·09 grms.) F. G. Cylinder perfectly tight. Colour and fracture dark grey, nearly black; but in places both surface and fracture light grey. No appearance of yellow anywhere in this deposit. All the residues, so far, of F. G. differ very considerably in appearance both from pebble and R. L. G.

The deposit on the sides was exceedingly thin, not more than ·01 inch in thickness.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·4258	·1667	·0417	·222	9·98

(This pressure rejected.)

Experiment 20, August 28, 1872.—Fired, in cylinder No. 6, 7930 grs. (513·86 grms.) F. G. Cylinder was absolutely tight. Gas collected in the usual manner. On opening the cylinder and removing the firing-plug, observed that the little button of residue adhering to the firing-plug, when cut into, had a large well-defined crystalline structure, the crystals being transparent although the surface of the button was dark grey. Sealed a portion in a tube for examination.

Residue in mass at bottom of cylinder as usual; next to nothing on sides. Colour and fracture much the same as in the last experiment, but the centre much lighter grey.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·5322	·1667	·0834	·145	15·8

(This pressure rejected.)

Experiments 21 to 24.—These experiments discarded.

N.B.—From Experiment 16 inclusive, the crusher-gauge was put loose in the charge of powder to be fired; but it having been found that the crusher-gauge was heated to such an extent as to soften the copper cylinder and thereby affect the observations, these experiments were repeated, as far as regards the pressure determinations, in Experiments 25 to 32.

Experiment 25, October 1, 1872.—Fired 2974 grs. (192·72 grms.) F. G. in cylinder No. 7.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·3860	·0834	·0417	·051	7·68

Experiment 26, October 17, 1872.—Fired 1586 grs. (102·77 grms.) F. G. in cylinder No. 6.

δ.	A.	a.	Crush, tin cylinder.	Pressure in tons.
·1064	·0834	·0417	·016	0·96

Experiment 27, October 18, 1872.—Fired 3172 grs. (205·55 grms.) F. G. in cylinder No. 6.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·2129	·0834	·0417	·008	3·0

Experiment 28, October 18, 1872.—Fired 4758 grs. (308·32 grms.) F. G. in cylinder No. 6.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·3193	·0834	·0417	·032	6·32

Experiment 29, October 19, 1872.—Fired 6344 grs. (411·09 grms.) F. G. in cylinder No. 6.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·4258	·0834	·0417	·074	9·34

Experiment 30, October 21, 1872.—Fired 7930 grs. (513·86 grms.) F. G. in cylinder No. 6.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·5322	·0834	·0417	·104	11·48

Experiment 31, October 29, 1872.—Fired 3507·5 grs. (227·286 grms.) F. G. in cylinder No. 7.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·4615	·0833	·0417	·065	8·68

Experiment 32, October 31, 1872.—Fired 3719 grs. (240·991 grms.) F. G. in cylinder No. 7.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·4893	·0833	·0417	·085	10·14

Experiment 33 (repetition).—Fired 2980 grs. (193·104 grms.) P. in cylinder No. 6.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·200	·0833	·0417	·006	2·70

Experiment 34 (repetition).—Fired 4470 grs. (289·656 grms.) P. in cylinder No. 6.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·300	·0833	·0417	·020	5·40

Experiment 35.—Fired 4560 grs. (295·488 grms.) P. in cylinder No. 7.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·600	·0833	·0417	·136	13·78

Experiment 36.—Fired 4560 grs. (295·488 grms.) P. in cylinder No. 7. Gas escaped.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·600	·0833	·0417	·132	13·50

Experiment 37, November, 26, 1872.—Fired 4560 grs. (295·488 grms.) P. in cylinder No. 7.

On firing, a slight quantity of gas escaped with a puff. Gas collected. Surface of the deposit was rough and dark-looking. Fracture grey, with greenish-yellow patches in places; hardly any deposit on sides.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·600	·0833	·0417	·150	14·80

Experiment 38, November 28, 1872.—Fired 5320 grs. (344·736 grms.) P. in cylinder No. 7.

A good deal of gas escaped through the gas-hole. Gas collected as usual. On opening, all the residue was found at the bottom; but in cooling the residue had contracted very much, separating on one side from the cylinder and leaving a considerable crack. The surface had a frothy appearance, as if occluded gas had been given off while still fluid. Colour dark grey on surface. Texture much more open than usual. Very much less yellow than in last experiment, and darker in colour than in Experiment 36, from which the gas escaped. Examined the colour carefully next day, and found it had become more yellow, although not so yellow as the residue in Experiment 37.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·7000	·0833	·0417	·203	18·60

Experiment 39, November 29, 1872.—Fired 4560 grs. (295·488. grms.) R. L. G. in cylinder No. 7. Cylinder was perfectly tight. Residue all at bottom, and firmly attached to sides. Surface level, but little dark roughnesses all over it. Colour and fracture much the same as in last experiment, but a little more grey.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·6000	·0833	·0417	·144	14·36

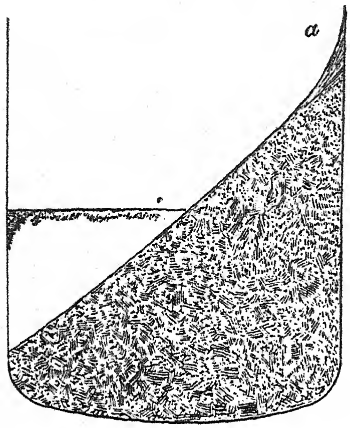
Experiment 40, December 2, 1872.—Fired 4560 grs. (295·488 grms.) F. G. in cylinder No. 7.

Cylinder tight, but a slight smell of sulphuretted hydrogen perceptible. Thirty seconds after explosion the cylinder was placed at an angle of 45°, and retained there for two minutes. When cylinder was opened the deposit was found lying at this angle, the surface being smooth and the edges sharply defined. Hence the deposit must have been perfectly fluid half a minute after explosion, and perfectly set two minutes later. Surface of deposit dark greenish grey; fracture much the same colour, and considerably darker either than that of R. L. G. or P. The bottled deposit had a powerful smell of ammonia.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·6000	·0833	·0417	·141	14·14

Experiment 41, December 3, 1872.—Fired 5320 grs. (344·736 grms.) R. L. G. in cylinder No. 7.

One minute after firing, the cylinder was placed at an angle of 45°. Forty-five seconds later the position of the cylinder was reversed.



Cylinder quite tight. On opening, it was found that one minute after explosion the deposit had just commenced to congeal on the top, a thin crust having been formed, which was broken through when the cylinder was returned to its original position; but a considerable portion of the crust was left. The sharpness with which the cylinder had struck its rest had made the deposit run up the side, as at *a*. Hence, a minute after explosion, the deposit was in a very fluid state, but had just begun to set. It could not, as evidenced by the mark at *a*, have been viscid. Forty-five seconds later the deposit was perfectly set. Colour dark grey with a dark olive-green hue. A few cavities in the deposit.

δ.	A.	*a*.	Crush, copper cylinder.	Pressure in tons.
·7000	·0833	·0417	·216	19·54

Experiment 42, December 4, 1872.—Fired 5320 grs. (344·736 grms.) F. G. in cylinder No. 7.

Cylinder tight, but slight smell of SH_2. On opening the cylinder, the nose of the crusher-plug was found to have broken off, and it lay loose on the top of the deposit, showing that it must have fallen off after the deposit was solid. Crusher covered with slight deposit and numerous small crystals, apparently sulphide of iron. Deposit more like that of P. and R. L. G. than formerly. The bottled residue smelt most powerfully of ammonia, too powerfully to hold to the nose.

δ.	A.	*a*.	Crush, copper cylinder.	Pressure in tons.
·7000	·0833	·0417	·197	18·2

Experiment 43, December 5, 1872.—Fired 6080 grs. (393·984 grms.) pebble-powder in No. 7 cylinder.

Cylinder perfectly tight.

δ.	A.	*a*.	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0833	·126	28·6

Experiment 44, December 6, 1872.—Fired 6080 grs. (393·984 grms.) R. L. G. in cylinder No. 7.

A small quantity of gas leaked shortly after explosion. Deposit had a great many bright crystals (sulphide of iron) diffused through it.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0833	·100	24·4

Experiment 45, December 17, 1872.—Fired 6080 grs. (393·984 grms.) F. G. in cylinder No. 7.

Gas escaped past cone.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0833	·092	23·2

Experiment 46, December 24, 1872.—Fired 3800 grs. (246·286 grms.) R. L. G. in cylinder No. 7.

The weight of the mild steel cylinder was 72,688 grms. After firing, the cylinder being perfectly tight, 9912 grms. water were added.

	Fahr.	Cent.
The temperature of the cylinder before firing was	54°·15	(12°·28).
The temperature of the water before firing was .	55°·75	(13°·20).

After firing, the following observations of temperature were made, that of the room in which the observations were made being 56° Fahr. (13°·35 Cent.):—

	Fahr.	Cent.
Temperature of water before explosion .	55°·75	(13°·20).
„ „ 5 min. after explosion	67°·0	(19°·4).
„ „ 10 „ „	70°·8	(21°·5).
„ „ 15 „ „	71°·1	(21°·66).
„ „ 20 „ „	71°·2	(21°·71).
„ „ 25 „ „	71°·0	(21°·6).
„ „ 30 „ „	70°·8	(21°·5).
„ „ 35 „ „	70°·5	(21°·35).
„ „ 40 „ „	70°·5	(21°·35).
„ „ 45 „ „	70°·4	(21°·30).
„ „ 50 „ „	70°·3	(21°·25).

Since in twenty minutes the mass cooled by 0°·7, this amount should be added to the maximum temperature of the water.

At fifty-five minutes after the explosion the gases were suffered to escape, and water taken from the calorimeter was placed in the

cylinder. The temperature of the water was found to be 69°·4 Fahr. (20°·72 Cent.). *N.B.*—Volume of deposit = 1180 grs. (76·464 c.c.).

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·5000	·0833	·0417	·090	10·48

Experiment 47, December 28, 1872.—Fired 6080 grs. (393·978 grms.) F. G. in same cylinder as was used in last experiment. After firing, the cylinder was at once placed in a vessel prepared for it, filled with water. There was a slight crackling sound, but no escape of gas, except a few minute bubbles, which, however, soon ceased.

Weight of cylinder	72,688·0 grms.
„ water	15,340·0 „
Temperature of cylinder before experiment .	57°·5 Fahr.
„ water „ .	60°·45 Fahr.

and the heat generated by the explosion raised the common temperature of the cylinder and water to 80°·45 Fahr. (26°·87 Cent.). Hence the steel was raised through 22°·95 Fahr. = 12°·75 Cent.; water through 20°·00 Fahr. = 11°·11 Cent.

Residue and gas collected from this experiment.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0833	·117	27·1

Experiment 48.—Fired 3800 grs. (246·286 grms.) F. G. in same cylinder as before, and with the same arrangements. On placing the cylinder in the water, a few very small bubbles escaped from the firing-plug, and this slight escape continued during the experiment.

Weight of cylinder	72,688·0 grms.
„ water	14,158 „
Temperature of cylinder before experiment .	56°·5 Fahr.
„ water „ .	59°·15 Fahr.

and the heat generated by the explosion raised the common temperature to 71°·9 Fahr. (22°·15 Cent.). Hence the steel was raised through 15°·4 Fahr. = 8°·555 Cent.; water through 12°·75 Fahr. = 7°·083 Cent.

Amount of deposit = 1038 grs. (67·262 c.c.). The deposit seemed to have contracted, since solidification, from ·2 to ·25 inch.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·5000	·0833	·0417	·090	10·48

Experiment 49.—Fired 6080 grs. (393·978 grms.) R. L. G. in same cylinder. Cylinder perfectly tight, but before placing in water crackling sound noticed.

Cylinder weighed	72,688 grms.
Water „	14,845 „
Temperature of cylinder before explosion .	46°·2 Fahr.
„ water „ .	51°·85 Fahr.
„ room	61° Fahr.

and the heat generated raised the common temperature of cylinder and water to 71°·32 Fahr. Hence steel raised through 25°·12 Fahr. = 13°·95 Cent.; water through 19°·47 Fahr. = 10°·82 Cent.

Amount of deposit = 1900 grs. (123·120 c.c.).

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0417	·265	23·2

Experiments 50 to 52.—These experiments were undertaken to measure the volume of gas produced by the explosion of a given weight of powder. The gas was allowed to escape into a gasometer charged with a saturated saline solution; but as it was found that a considerable quantity of gas was absorbed by the water, this apparatus was replaced by the more perfect one described in the body of the paper.

Experiment 53, February 6, 1873.—Fired 5960 grs. (386·2 grms.) P. powder in cylinder No. 6; measured the quantity of gas produced.

Quantity of gas produced	112,455·5 c.c.
Temperature of gas when measured . .	18°·3 Cent.
Barometric pressure	767 mm.

Experiment 54, February 7, 1873.—Fired 5960 grs. (386·2 grms.) P. powder, with same arrangements as in last experiment.

Quantity of gas measured	110,633·4 c.c.
Temperature of gas when measured . .	17°·2 Cent.
Barometric pressure	770 mm.

Experiment 55, February 8, 1873.—Fired 5960 grs. (386·2 grms.) R. L. G., with same arrangements.

Quantity of gas measured	110,269·6 c.c.
Temperature of gas when measured . .	16°·0 Cent.
Barometric pressure	774 mm.

Experiment 56, February 10, 1873.—Fired 5960 grs. (386·2 grms.) F. G. under same conditions.

Quantity of gas measured	104,875·3 c.c.
Temperature of gas	15°·0 Cent.
Barometric pressure	775 mm.

Experiment 57, February 11, 1873.—Fired 5960 grs. (386·2 grms.) F. G. under same arrangements.

Quantity of gas measured	103,345·2 c.c.
Temperature of gas	13°·3 Cent.
Barometric pressure	768 mm.

Amount of deposit measured, and found to occupy a space of 115·34 c.c. The deposit appeared not to have contracted much after solidification; but it had parted from the side, leaving a crack about 0·04 inch (1 mm.) wide.

Experiment 58, February 12, 1873.—Fired 5960 grs. (386·2 grms.) R. L. G. Same arrangements.

Quantity of gas measured	107,354·5 c.c.
Temperature of gas	14°·5 Cent.
Barometric pressure	772 mm.
Deposit occupied a space of	110·8 c.c.

Experiment 59.—Experiment on mode of closing firing-plug.

Experiment 60, March 5, 1873.—Fired 5960 grs. (386·2 grms.) P.

Quantity of gas	114,059·7 c.c.
Temperature of gas	19° Cent.
Barometric pressure	765 mm.
Deposit occupied a space of	111·78 c.c.

Experiment 61, March 6, 1873.—Fired 5960 grs. (386·2 grms.) R. L. G.

Quantity of gas	111,367·5 c.c.
Temperature of gas	15°·94 Cent.
Barometric pressure	755·6 mm.
Deposit occupied a space of	105·30 c.c.

Experiment 62.—Fired 5960 grs. (386·2 grms.) F. G.

Quantity of gas	108,881·8 c.c.
Temperature of gas	19°·61 Cent.
Barometric pressure	739·4 mm.
Deposit occupied a space of	108·5 c.c.

Experiment 63.—Fired 3800 grs. (246·286 grms.) R. L. G. to determine heat. Cylinder quite tight.

Cylinder weighed	72,688 grms.
Water "	15,655·4 grms.
Temperature of cylinder before explosion	51°·4 F. (10°·72 C.).
" water "	51·65 Fahr.
" room	52·5 Fahr.

The heat generated raised the temperature of water and cylinder to 64°·25 Fahr.

Hence steel raised through 12°·25 Fahr. = 7°·139 Cent.; water through 12°·6 Fahr. = 7°·0 Cent.

Experiment 64.—Fired 5960 grs. (386·2 grms.).

Quantity of gas	106,625·0 c.c.
Temperature of gas	16°·55 Cent.
Barometric pressure	758·2 mm.

Experiment 65.—Fired 6840 grs. (443·23 grms.) P. in cylinder No. 7. This charge filled the cylinder nearly quite full. Cylinder, on firing, cracked between the firing and crusher-plugs. Crack about ·5 mm. wide. Report very loud.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·900	·0833	·0833	·156	33·4

Experiment 66.—Fired 6840 grs. (443·23 grms.) P. In about a second after firing, the gas made a fizzing sound, and in about another second escaped by blowing out the gauge-plug with a loud report. Lower threads of the screw on the crusher-plug washed away by the escape of the gas.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·900	·0833	·0833	·145	31·6

Experiment 67.—Experiment on mode of detonating a charge.

Experiment 68.—Fired 6840 grs. (443·23 grms.) R. L. G. Cylinder and all parts perfectly tight. Residue and gas collected. Observed that the deposit had apparently not contracted much.

On the firing-plug were several congealed drops of deposit like icicles, and on the surface below, spots, which had apparently dropped from above, were visible.

Surface of deposit dark grey, almost black.

Fracture olive-green, with frequent spots of brilliant yellow, of the size of a pin's head.

Top part of deposit put in separate bottle from bottom part, each sample being ground and mixed carefully in an atmosphere of dry nitrogen.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·900	·0833	·0833	·168	35·6

Experiment 69, May 29, 1873.—Fired 6840 grs. (443·23 grms.) F. G. Cylinder, etc., perfectly tight. On opening the cylinder, found white crystals deposited on firing-plug. Deposit very dark, and more greasy than usual.

Fracture dark grey, with only few spots of yellow.

Deposit first taken did not heat; but there was great difficulty in getting it to grind in an atmosphere of dry nitrogen.

The portion we succeeded in grinding was sealed in test-tube, marked Experiment 69*a*. Unground portion sealed in test-tube, marked B. Bottom portions of the deposit, when exposed to the air, changed with great rapidity to a bright yellow on the surface, with development of heat. It was got as rapidly as possible into the mill, and was easily ground in dry nitrogen. This was sealed in bottle, marked C, while some unground lumps were marked D.

A mixture of the top and bottom was ground in nitrogen, and was marked E.

Transparent crystals (on firing-plug) also preserved in small tube.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·900	·0833	·0833	·118	27·2

Experiment 70, October 20, 1873.—Fired 3800 grs. (246·286 grms.) R. L. G. by means of a detonator containing 2 grms. of fulminate of mercury. Cylinder perfectly tight. Residue full of lustrous scales, otherwise of usual appearance; considerable lump of metal found in bottom (firing-wire and detonator-case).

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·500	·1667	·0833	·081	10·7

Experiment 71, October 22, 1873.—Last experiment repeated with similar results.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·500	·1667	·0833	·086	11·10

Experiment 72, October 24, 1873.—Fired, with a view to determine the amount of heat absorbed by a gun when fired, nine

rounds of 1 lb. 12 oz. (793·788 grms.) R. L. G. in a 12-pr. B.L. gun; weight of shot, 11 lbs. 12 oz. (5,329·72 grms.). Temperature of air, 46°·2 Fahr.

Time of firing, six minutes. After firing, the gun was at once placed in a vessel of water and the changes of temperature observed. The following are the data:—

Weight of gun . . .	387,141·6 grms.
Weight of water . . .	192,777·0 „

Temperature of gun and water before firing, 47°·0 Fahr.; the heat communicated to the gun by nine rounds raised the common temperature of the gun and water to 51°·15 Fahr.

Hence the heat raised the water and gun through 4°·15 Fahr. = 2°·305 Cent.

Experiment 73.—Fired five rounds 1·5 lb. (680·39 grms.) R. L. G. in a 12-pr. B.L. gun.

Weight of shot	532·75 grms.
Temperature of air	46°·5 Fahr.
Time of firing	$2\frac{1}{4}$ minutes.
Weight of gun	387,141·6 grms.
Weight of water	68,810·1 „
Temperature of gun and water before firing .	45°·7 Fahr.
„ „ „ after „ .	50°·55 Fahr.

Hence the heat communicated to the gun raised gun and water through . . . } 4°·85 Fahr. = 2°·694 Cent.

Experiment 74.—Exposed four crucibles filled with deposit from Experiment 36 to most intense heat of one of Siemens gas furnaces; one crucible uncovered, the rest covered. Temperature estimated at 1700° Cent. A portion of the residue spirted immediately and then became quiet. On removal from the furnace half an hour afterwards, a little vapour was observed coming from the crucibles. Their contents were perfectly liquid, setting at about 700° or 800° Cent.

The colour of the contents when cool was a bright sealing-wax red, similar to the deposit found in the chambers of guns, turning black on the surface on exposure to the air: sealed for examination.

Experiment 75, November 1, 1873.—Experiment 20 repeated, 3800 grs. (246·286 grms.) F. G., analysis of 20 being unsatisfactory. When exploded, cylinder perfectly tight; had to put a drop of water in gas-hole before gas would come away, the hole being sealed by the deposit.

Residue when got out very dark in colour; no yellow or green apparent when put in bottle; after grinding in nitrogen, a little heat appeared to be developed and a tinge of yellow appeared.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·5000	·1667	·0833	·076	10·2

Experiment 76, November 3, 1873.—Experiment 43 repeated, results of analysis of previous experiment being irreconcilable; 6080 grs. (393·986 grms.) P.

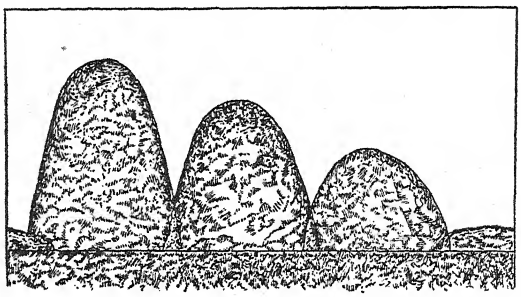
On opening the cylinder, observed that the contraction was greater than usual; nothing else remarkable.

δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0833	·098	24·2

Experiment 77, November 13, 1873.—Fired 6840 grs. (417·312 grms.) P. After firing, the cylinder was allowed to stand for 60 seconds, then tilted over to an angle of 45° and replaced. At 75 seconds after firing, it was again tilted on a different place, and so on up to 2 minutes.

On opening the cylinder it was found at 60 and 75 seconds after explosion the deposit was perfectly fluid; at 90 seconds it was rather thick, and at 105 seconds it hardly moved.

The development of the interior surface of the cylinder appeared thus (see figure).



δ.	A.	a.	Crush, copper cylinder.	Pressure in tons.
·9000	·0833	·0833	1·44	31·4

Experiment 78, January 12, 1874.—Fired 5320 grs. (344·74 grms.) in the same cylinder. On opening, the colour of the deposit was a lighter grey than usual. The contraction after setting appeared to be considerable, apparently ·2 inch.

In this experiment, before firing, a piece of the finest platinum wire,* also a piece of sheet platinum about 1 inch (26 mm.) square and ·03 inch (·76 mm.) thick, were placed among the powder. After the explosion, the thin platinum wire had disappeared, but small globules of the metal were found in many places welded to the surface of the cylinder.

The sheet platinum was not melted, but was doubled up; there were appearances, however, of fusion on its surface, and in places the platinum wire had been welded to the sheet. The weight of the sheet platinum was about 0·25 oz. (about 6 grms.).

δ.	A.	a.	Crush.	Pressure in tons.
·7	·0833	·0833	·067	18·9

Experiment 79, January 14, 1874.—Fired 5320 grs. (344·74 grms.) Spanish pebble-powder; put in a coil of platinum wire ·06 inch (1·52 mm.) in diameter, weighing about 15 grms.

The platinum after the explosion was found in a lump at the bottom of the deposit thoroughly fused, with the exception of a small portion. Colour and appearance of residue rather different from the ordinary. There were a good many light-coloured splotches. The surface of the deposit was broken and rough, as if by the escape of gas.

δ.	A.	a.	Crush.	Pressure in tons.
·700	·0833	·0833	·056	17

Experiment 80, January 16, 1874.—Fired 5960 grs. (386·21 grms.) R. F. G.

Quantity of gas measured	109,540 c.c.
Temperature of gas	18°·33 Cent.
Barometric pressure	729 mm.

Experiment 81.—Fired 5960 grs. (386·21 grms.) pebble (Spanish).

Quantity of gas measured	98,607·7 c.c.
Temperature of gas	16°·67 Cent.
Barometric pressure	735 mm.

Experiment 82.—Placed in a Siemens furnace, at a temperature of about 1700° Cent., two crucibles, one containing powder-residue, the other equal weights of potassium carbonate and liver of sulphur. On first placing them in the furnace a little ebullition took place, apparently in both crucibles, but with some violence in the crucible

* Wound round the sheet platinum.

with powder-residue. This ebullition, however, soon subsided, and a slow volatilisation appeared to proceed. On taking the crucibles from the furnace, the height of the contents (which left marks on the crucibles) was noted, and the volume of the deposit and the amount of contraction were measured by means of mercury, with the following results:—

Powder-residue.

Volume at 1700° Cent.	=	17·859	c.c.
Volume at 0° Cent.	=	10·044	„
		7·815	„

Expansion between 0° and 1700° = 7·815 c.c. = 77·8 per cent.

Potassium carbonate and liver of sulphur.

Volume at 1700° Cent.	=	28·188	c.c.
Volume at 0° Cent.	=	14·580	„
		13·608	„

∴ Expansion between 0° Cent. and 1700° Cent. = 13·608 = 93·3 per cent.

With the above two crucibles there was also a third, containing powder-residue, and in this crucible a piece of platinum was placed. The expansion measured was over 100 per cent., but could not be depended on, on account of the platinum. The metal was not appreciably altered by the heat.

Experiment 83.—Experiment 79 repeated.

Experiment 84.—Fired 5320 grs. (344·74 grms.) F. G. in small cylinder. Put a piece of platinum wire 4 inches long (100 mm.), 16 W. G. (1·5 mm. in diameter), with the powder. This wire showed signs of fusion on the surface, but was not at all melted.

Experiment 85, February 18, 1874.—Fired 5320 grs. (344·736 grms.) R. L. G. in cylinder. Placed in cylinder a piece of platinum wire 4 inches (100 mm.) long and 0·04 inch (1 mm.) in diameter. The wire was superficially fused, but otherwise little altered. No crusher used, the gauge having been destroyed in Experiment 83.

Experiment 86, February 19, 1874.—Fired 5320 grs. (344·736 grms.) R. L. G. in same cylinder. Placed in the cylinder a piece of platinum wire of same dimensions as in last experiment, also the same length of copper wire, 0·13 inch (3·2 mm.) in diameter. The copper was completely fused, and firmly attached to the cylinder, it being found necessary to remove it with a chisel. The platinum wire was superficially fused, as in the last experiment.

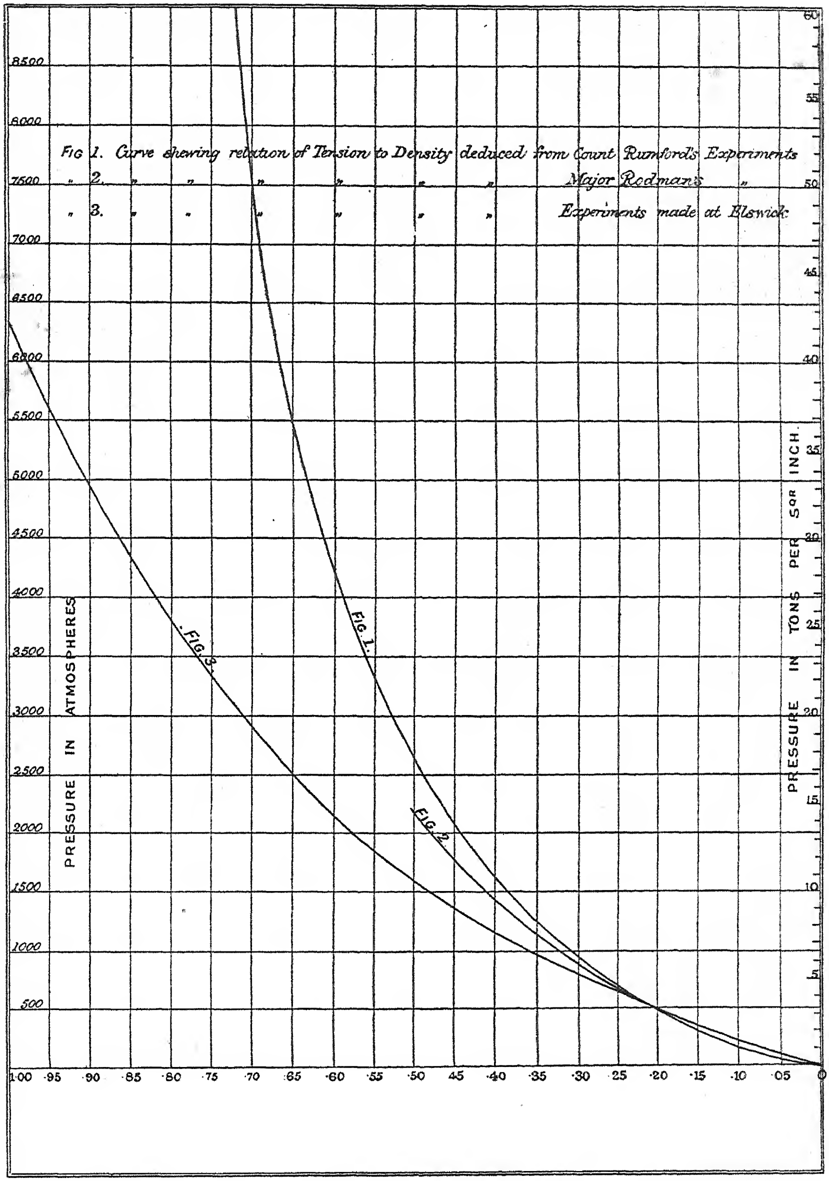


FIG 1. Curve shewing relation of Tension to Density deduced from Count Rumford's Experiments
" 2. " " " " " " Major Rodman's "
" 3. " " " " " " Experiments made at Elswick
PRESSURE IN ATMOSPHERES
PRESSURE IN TONS PER SQR INCH.
FIG. 1.
FIG. 2.
FIG. 3.
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
60
55
50
45
40
35
30
25
20
15
10
5
1·00
·95
·90
·85
·80
·75
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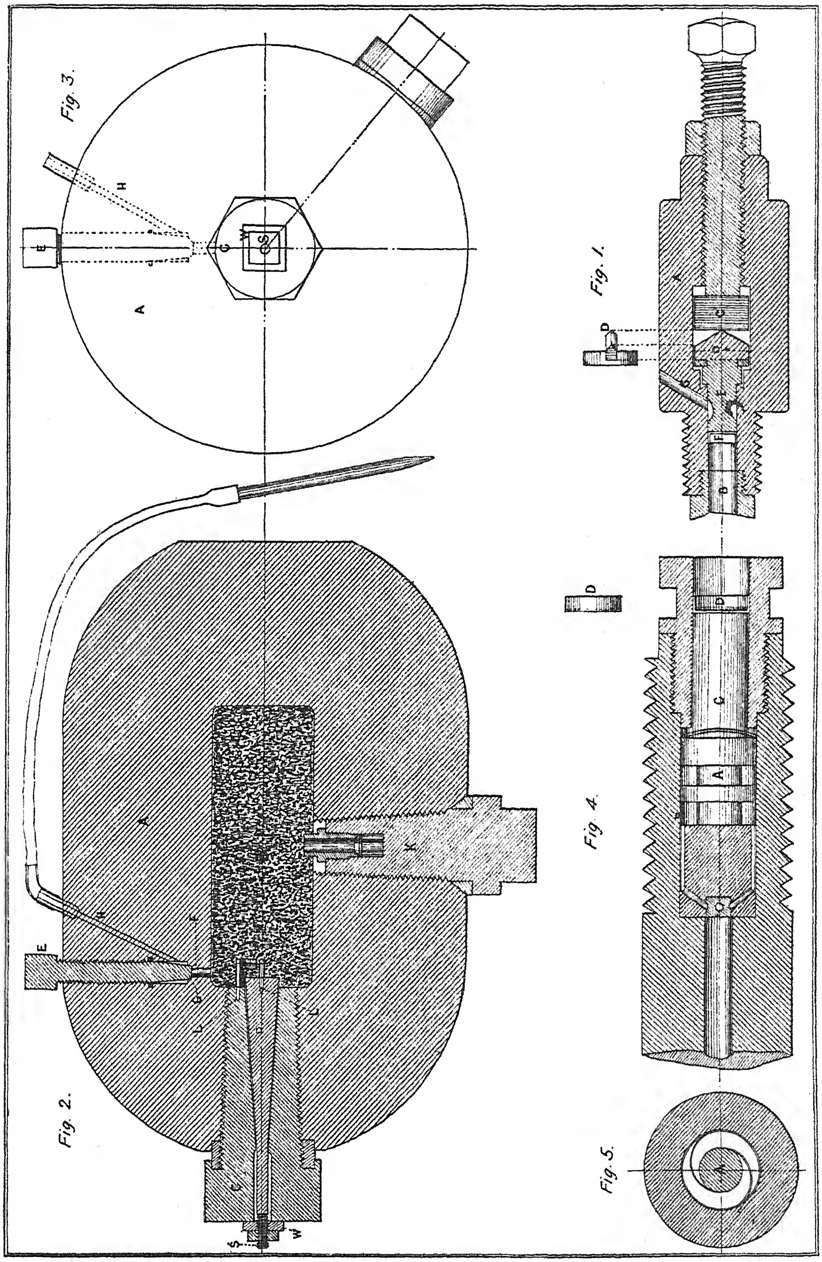
·30
·25
·20
·15
·10
·05
0



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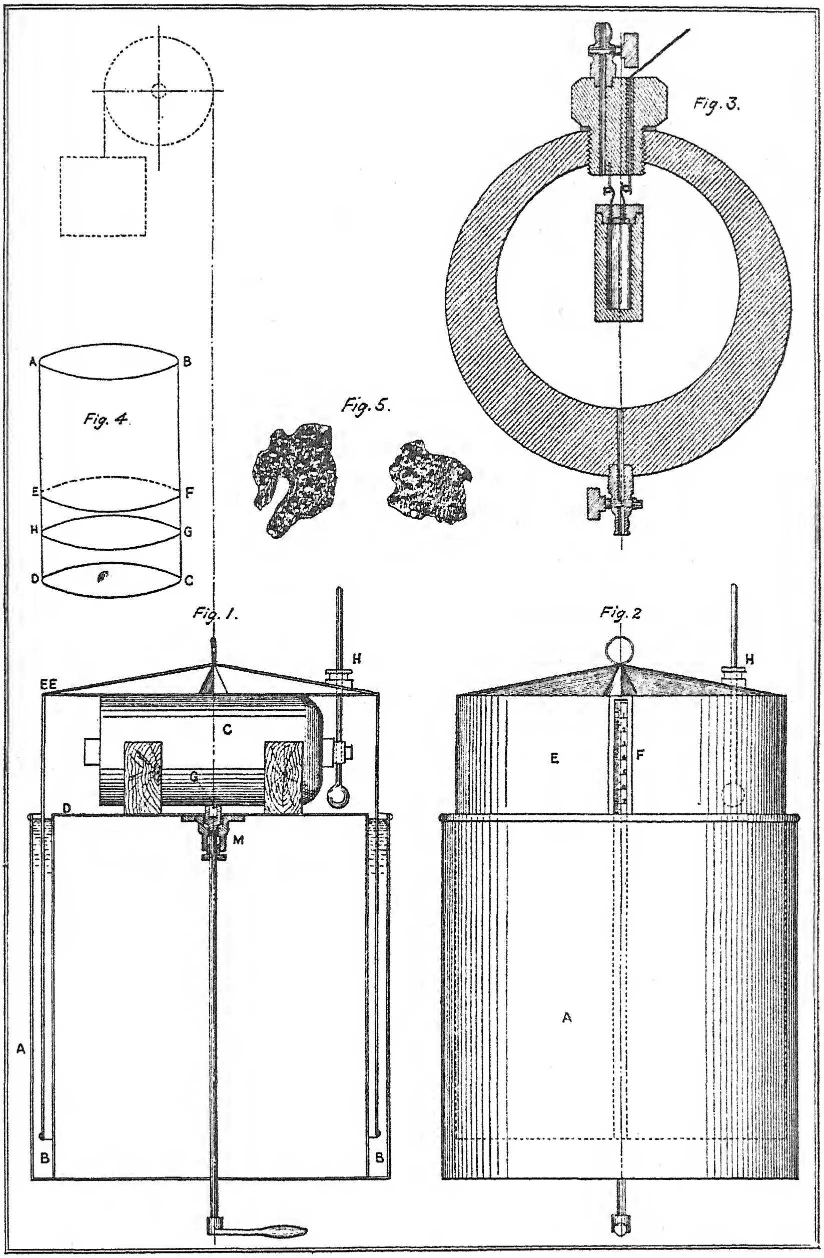

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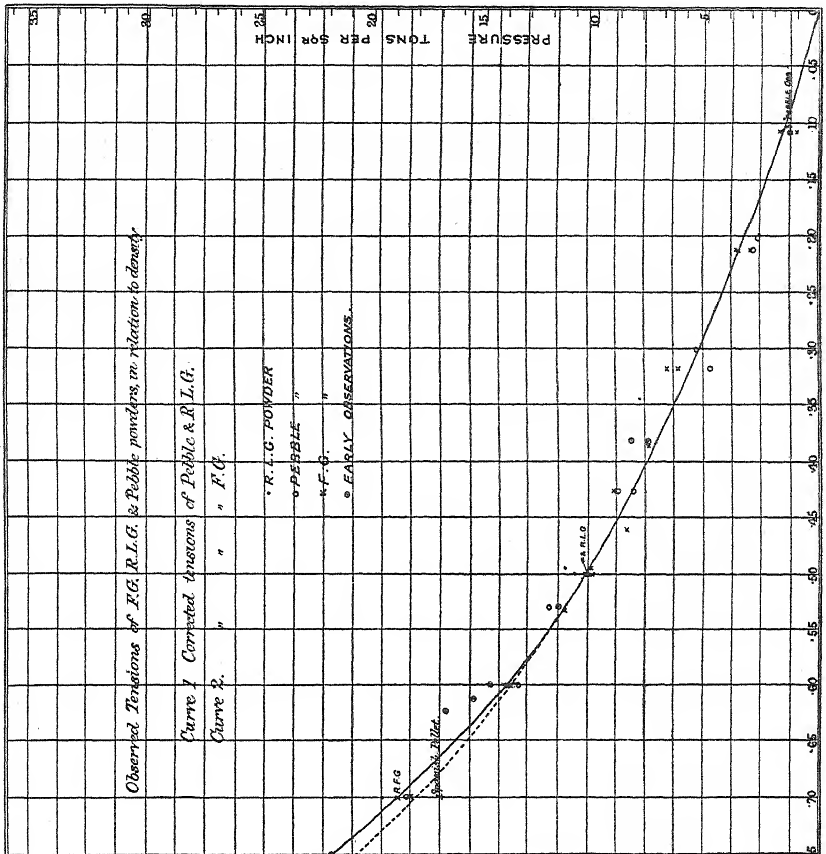
Observed Tensions of F.G. R.L.G. & Pebble powders, in relation to density
Curve 1 Corrected tensions of Pebble & R.L.G.
Curve 2. " " " F.G.
· R.L.G. POWDER
o PEBBLE "
x F.G. "
⊙ EARLY OBSERVATIONS.
PRESSURE TONS PER SQR INCH
PRESSURE IN ATMOSPHERES
PEBBLE & R.L.G.
F.G.
PELLET
R.F.G
Spanish Pellet
R.L.G.

[To face p. 230.

PLATE XIII.

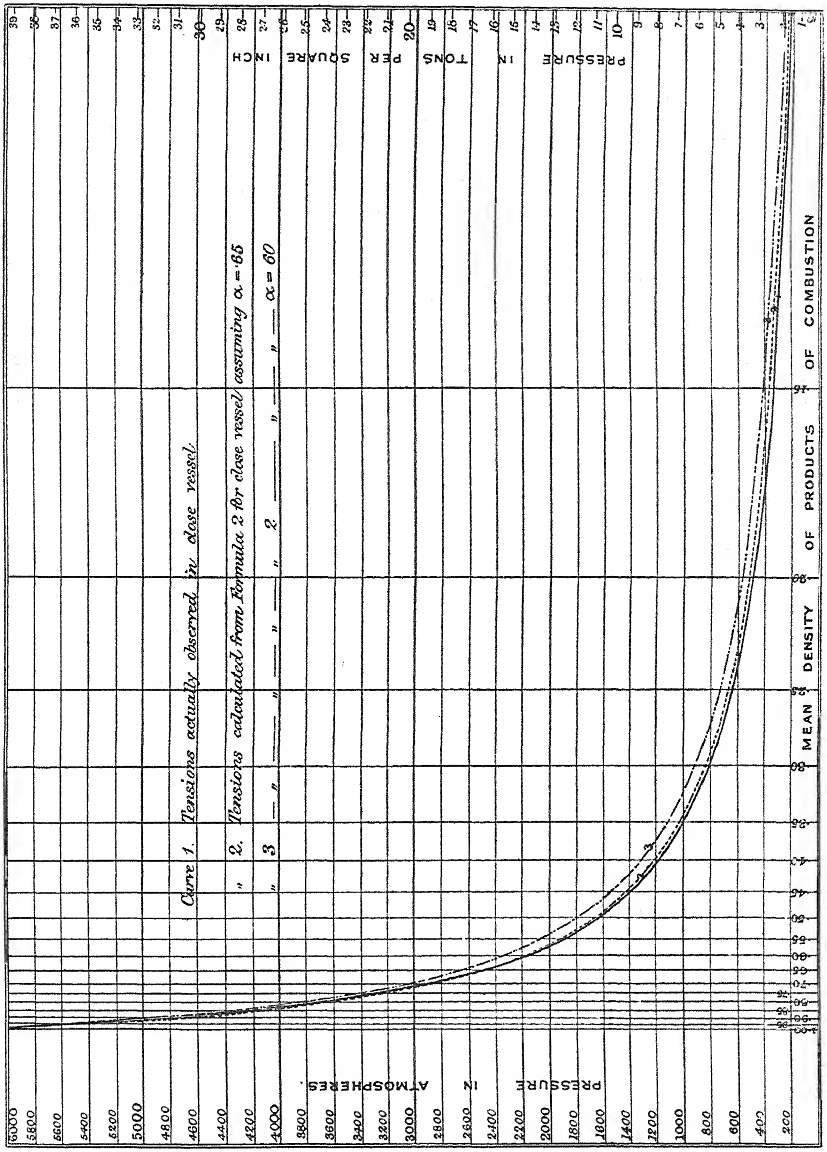

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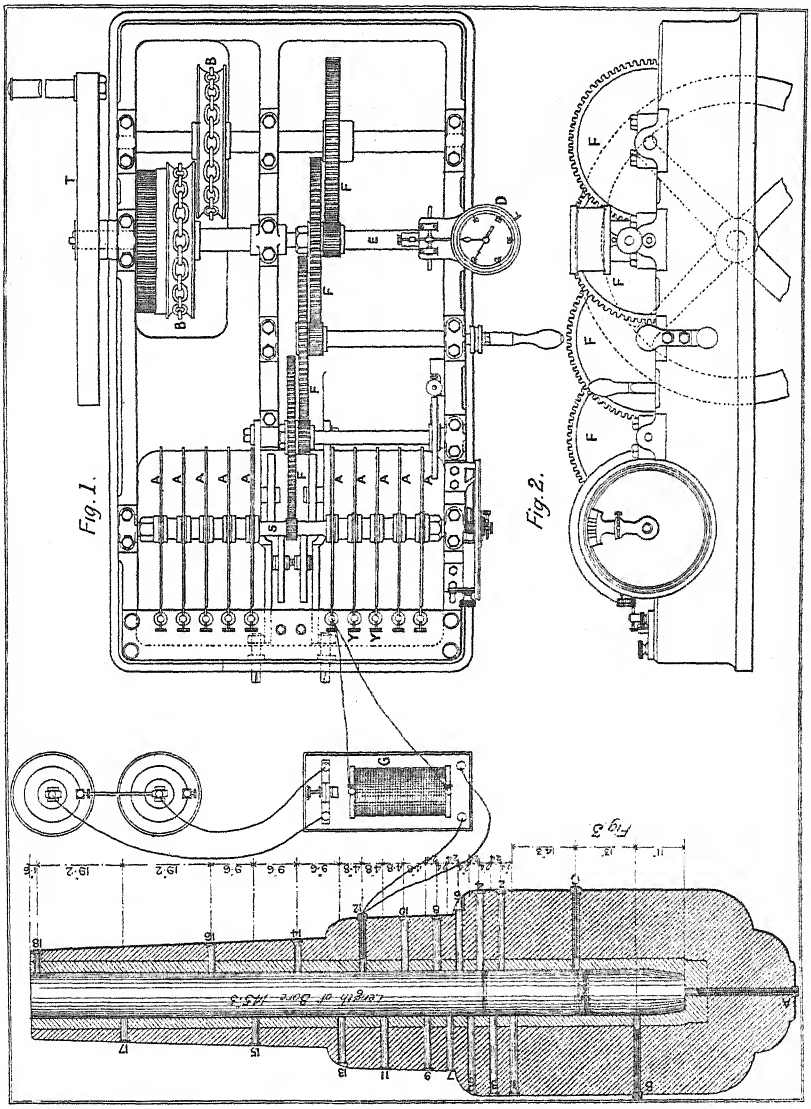
PLATE XIV.



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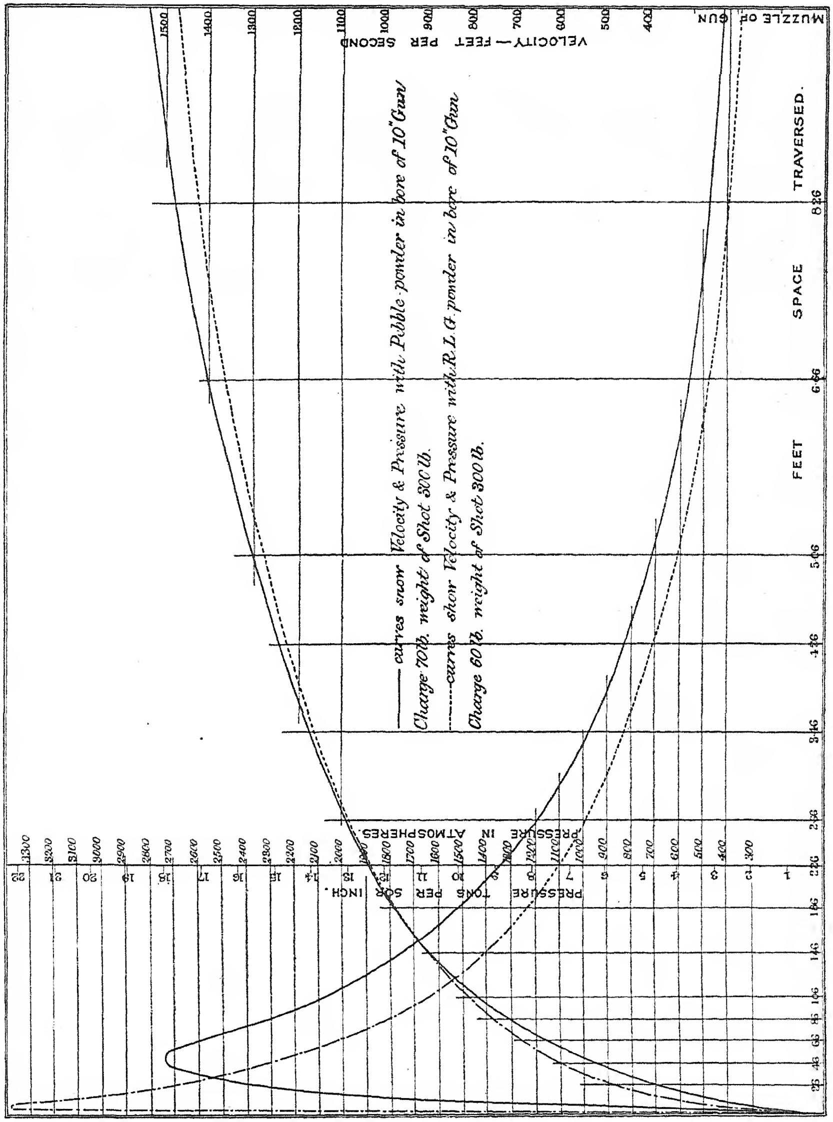
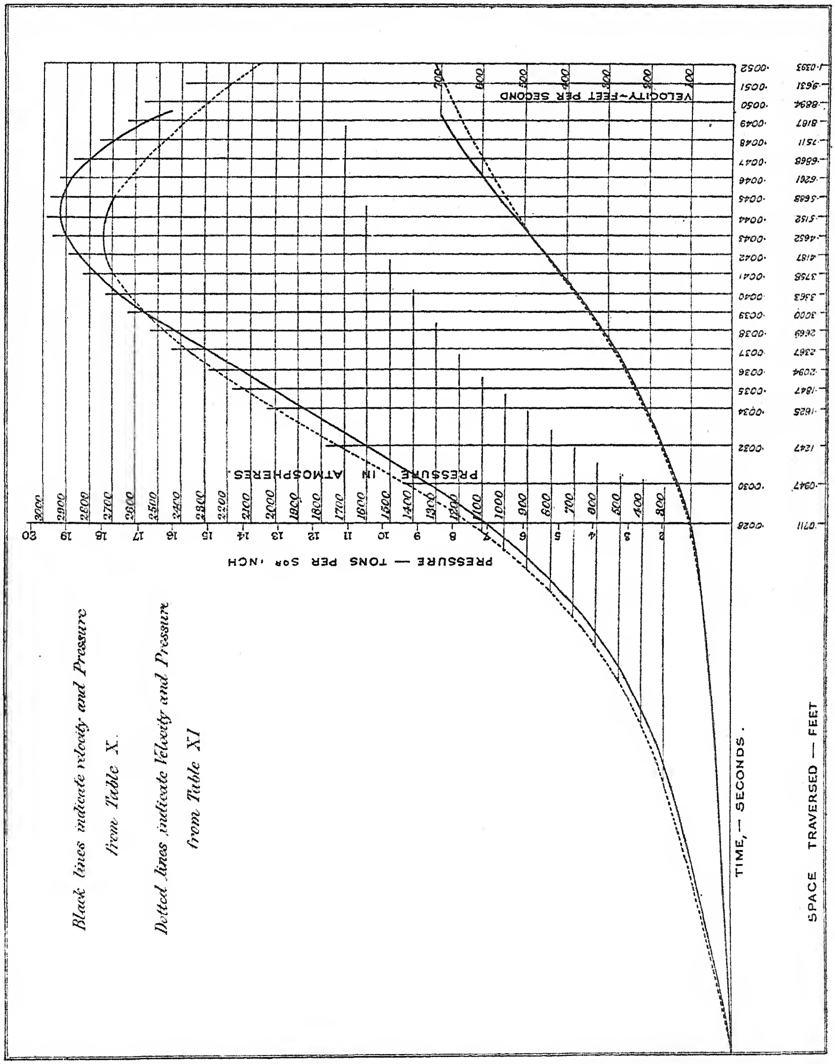
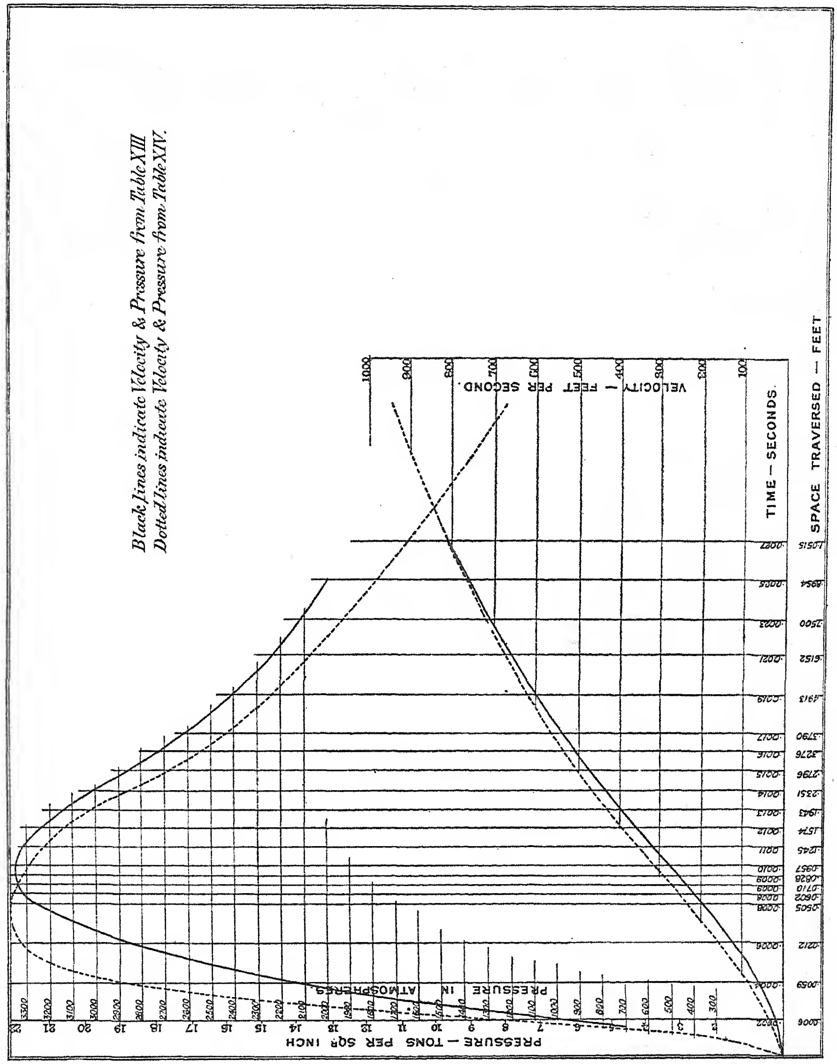

curves show Velocity & Pressure with Pebble powder in bore of 10" Gun
Charge 70 lb. weight of Shot 300 lb.
curves show Velocity & Pressure with R.L.G. powder in bore of 10" Gun
Charge 60 lb. weight of Shot 300 lb.
VELOCITY — FEET PER SECOND
PRESSURE IN ATMOSPHERES
PRESSURE TONS PER SQR INCH.
MUZZLE OF GUN
SPACE TRAVERSED. FEET

[To face p. 230.


Black lines indicate velocity and Pressure from Table X.
Dotted lines indicate Velocity and Pressure from Table XI
VELOCITY—FEET PER SECOND
PRESSURE IN ATMOSPHERES
PRESSURE — TONS PER SQR. INCH
TIME, — SECONDS.
SPACE TRAVERSED — FEET

[To face p. 230.

PLATE XVII.



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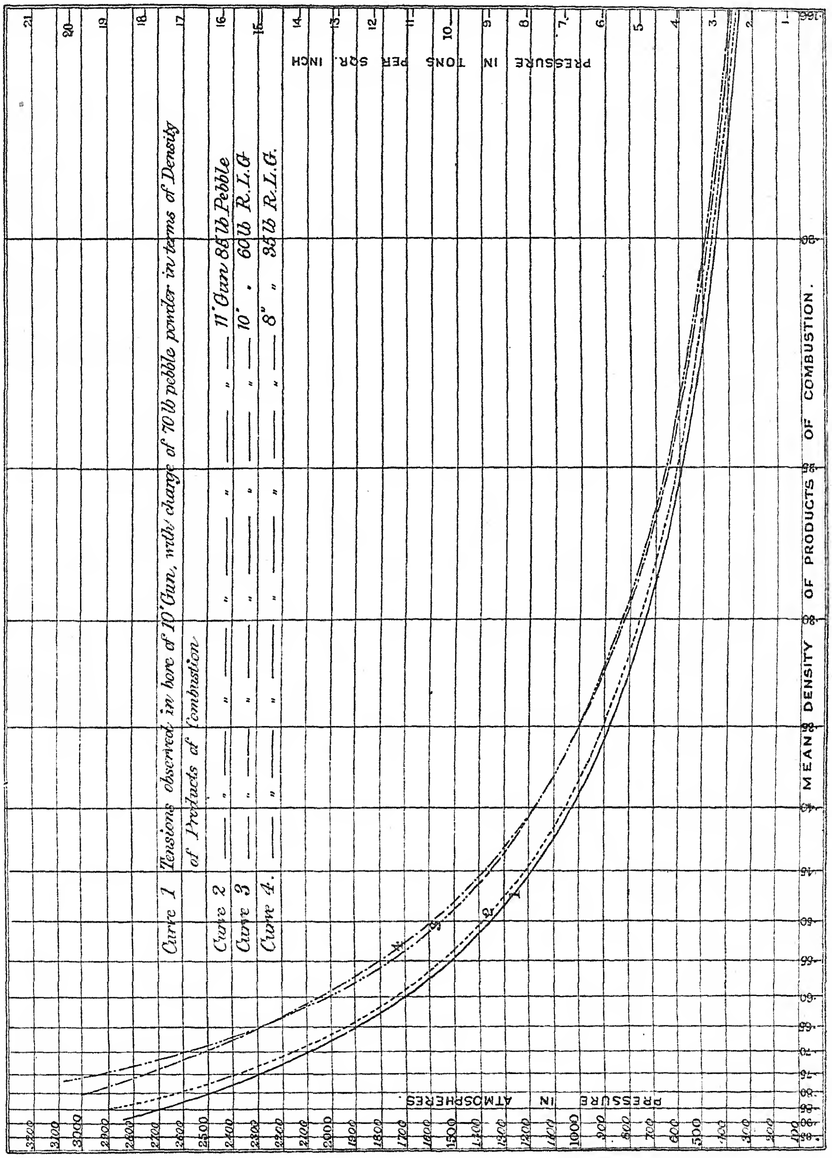
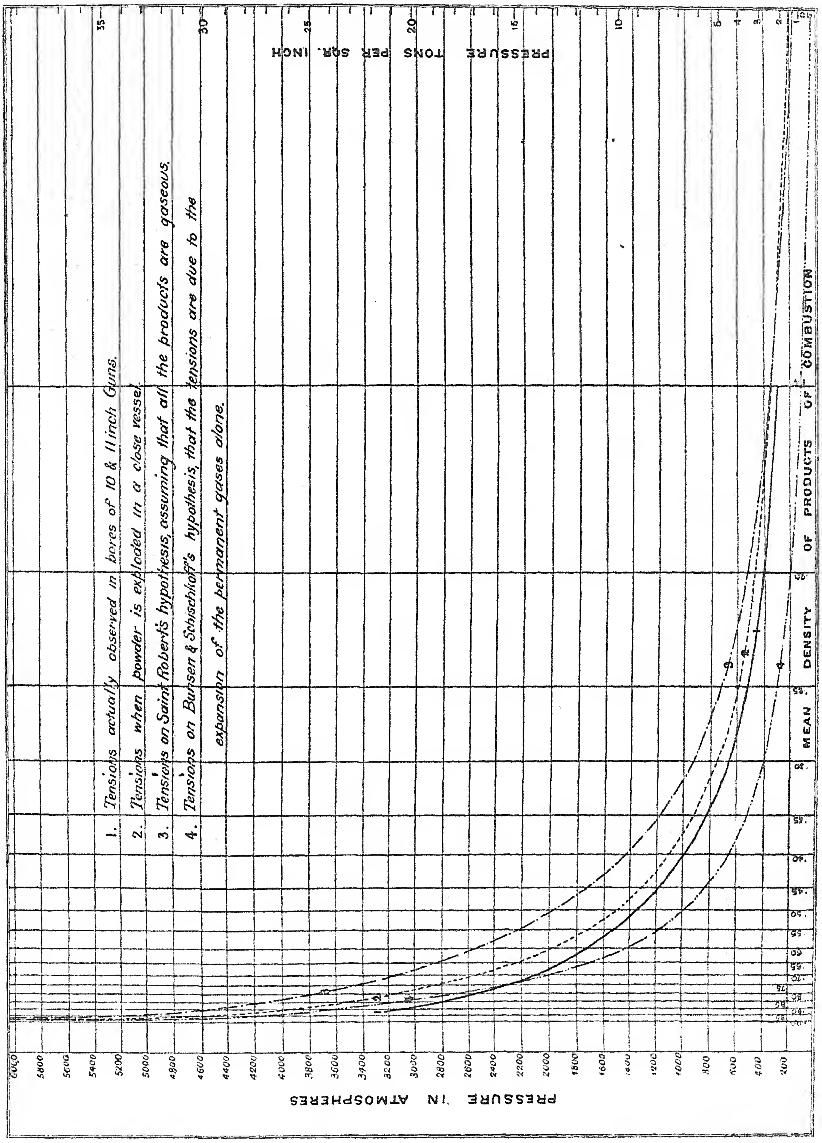

Curve 1 Tensions observed in bore of 10" Gun, with charge of 70 lb pebble powder in terms of Density of Products of Combustion
Curve 2 " " " " 11" Gun 85 lb Pebble
Curve 3 " " " " 10" " 60 lb R.L.G.
Curve 4 " " " " 8" " 35 lb R.L.G.
MEAN DENSITY OF PRODUCTS OF COMBUSTION.
PRESSURE IN TONS PER SQR. INCH
PRESSURE IN ATMOSPHERES.

[To face p. 230.]

PLATE XIX.



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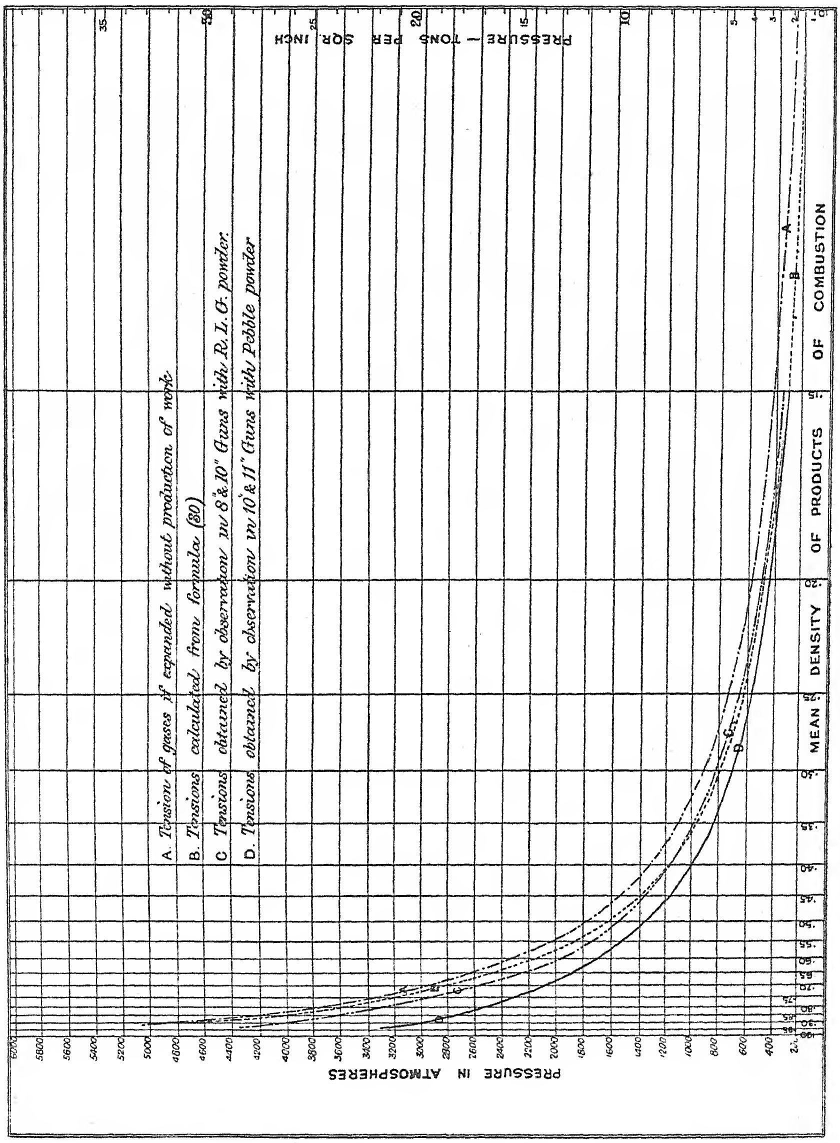
A. Tension of gases if expanded without production of work
B. Tensions calculated from formula (80)
C Tensions obtained by observation in 8" & 10" Guns with R.L.G. powder.
D. Tensions obtained by observation in 10" & 11" Guns with Pebble powder
PRESSURE — TONS PER SQR. INCH
PRESSURE IN ATMOSPHERES
MEAN DENSITY OF PRODUCTS OF COMBUSTION

[To face p. 230.

RESEARCHES ON EXPLOSIVES.—Part II.

(Fired Gunpowder—*Continued.*)

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During the course of the experiments that we have undertaken in extending our researches on explosives to the investigation of the action and results of fired guncotton, we have had occasion to

examine some points connected with the subject of our former memoir on "Fired Gunpowder"; and as the attention which the researches described in that memoir have received, especially on the Continent, is an evidence both of the theoretical and practical importance of our subject, we propose, prior to laying before the Society our researches on guncotton, to discuss a few points of considerable interest which have arisen out of our former investigations, and to give the results of some further experiments on gunpowder.

The Academy of Sciences of France having done us the honour to appoint a Commission to report on our researches, there have appeared in the *Comptes Rendus* a joint report* by General Morin and M. Berthelot, and two† separate memoirs on certain chemical points by the latter savant.

The high appreciation of our labours shown by the Academy has induced us to pay special attention to one or two points mentioned by the distinguished reporters as being open to discussion; we will now proceed to consider them, and to detail some further experiments calculated to throw light upon the different questions raised.

The principal points to which General Morin and M. Berthelot draw attention, are—

1. Potassium hyposulphite has been found as one of the products of combustion of gunpowder by every recent investigator. But the question arises, Is this product either wholly or in part primary? Or is it to be considered as secondary, formed from the primary products during the rapid loss of heat to which they are exposed? Or is it, finally, to be considered only as formed from the sulphide by the absorption of oxygen, during the processes of removal from the cylinder and of analysis, and therefore to be regarded as an accidental product?

2. In the memoir in question we stated that, according to our view, "any attempt to express, even in a complicated chemical equation, the nature of the metamorphosis which a gunpowder of average composition may be considered to undergo, would only be calculated to convey an erroneous impression as to the simplicity or definite nature of the chemical results and their uniformity under different conditions, while possessing no important bearing upon an elucidation of the theory of the explosion of gunpowder."

M. Berthelot, however, in a memoir upon the explosion of powder, based on our results, proposes to represent these results by a system

* *Comptes Rendus*, tom. lxxxii., p. 487. † *Idem.*, pp. 400 and 469.

of simultaneous equations expressing the chemical metamorphosis undergone by powder, at least as far as regards its fundamental products.

3. In the joint report of General Morin and M. Berthelot, and in the separate memoir above referred to of M. Berthelot, special attention is called to the heat disengaged by the explosion, and our determination, presented, as the reporters point out, with some reserve, is considered to be too low, partly because the apparatus used did not admit of extreme delicacy, and partly because higher determinations have been made by M. Tromenec and MM. Roux and Sarrau.

We now proceed to the discussion at length of these points, prefacing our remarks by Tables 1 and 2 hereto annexed (see pp. 235, 236, and 237).

Table 1, in addition to giving the results of one or two analyses which had not been completed when our first memoir was published (we have not considered it necessary to repeat the portions of this table already published), shows the mean percentage composition, by volume, of the gases, and the mean percentage composition, by weight, of the solid residues for each of the three principal powders examined by us. It also shows the highest and lowest proportions in which, with each powder, any particular product occurs, and gives the results obtained from the examination of the products of combustion of four descriptions of powder differing in many respects from the powders which formed the main subject of our memoir.

Table 2 contains the complete results of all our analyses; it shows the proportion by weight of each solid and gaseous product, and includes also the amount of water pre-existent in the various specimens of powder operated on.

A careful examination into the nature and proportions of the products furnished by the explosion of three descriptions of service gunpowder, differing but little in composition from each other, and by one and the same sample of powder under different conditions as regards pressure (or space in which the explosion took place), led us to the conclusion, which it may be as well to repeat in the precise terms used in our former memoir, namely, that "any attempt to express, even in a comparatively complicated chemical equation, the nature of the metamorphosis which a gunpowder of average composition may be considered to undergo when exploded in a confined space, would . . . only be calculated to convey an erroneous impression as to the simplicity or

the definite nature of the chemical results, and their uniformity under different conditions" (p. 146).

In giving expression in the foregoing terms to this conclusion, we certainly did not intend to convey the impression, nor do we consider that our words are at all susceptible of the interpretation, that it was impossible to put into some form of equation (as was done, for instance, by Bunsen and Schischkoff in the case of the analytical results arrived at by them), a representation of a variety of reactions, which if *assumed* to take place simultaneously among different proportions of the powder-constituents, might express results approximating to one or other of the analytical results obtained by us, and might thus afford some approximate theoretical representation of the metamorphosis of gunpowder when fired in closed vessels.

But the very great variations in composition (of the solid portion more especially) of the products of explosion of samples of gunpowder presenting only small differences in constitution, afforded, in our opinion, most conclusive proof that the reactions which occur among the powder constituents are susceptible of very considerable variations, regarding the causes of which it appears only possible to form conjectures, and that consequently "no value whatever can be attached to any attempt to give a general chemical expression to the metamorphosis of gunpowder of normal composition."

In one of the series of interesting communications made by M. Berthelot to the Academie des Sciences in 1876,* as contributions to the "History of Explosive Agents," that chemist gives to our conclusions, as expressed in our former memoir, an interpretation which, as above pointed out, they certainly cannot be considered to bear, when he says we have stated that the variations in the proportions of the principal products of explosion are opposed "to all general chemical representation of the metamorphosis produced by the explosion," an opinion contrary, as he states, to all that is known in chemistry. Starting with the above assumption of the nature of our views, M. Berthelot proceeds to demonstrate that, in order to account for the formation of the *chief* products in some particular proportion in which potassium sulphate is so small as to allow of its being neglected, the powder-constituents must be presumed to react upon each other simultaneously, in prescribed proportions, according to *three*, or, if the sulphate amount to 12 or 14 per cent., according to *four* out of *five* different theoretical reactions, which, if assumed to occur simultaneously, in variable proportion and number, M. Berthelot

* *Comptes Rendus*, tom. lxxxii., p. 400.

Table 1.*—*Showing the mean analytical results obtained from an examination of the solid and gaseous products of decomposition of Pebble, R. L. G., and F. G. powders; showing also the same particulars with respect to four other powders.*

Nature of powder.		Mean density of products of combustion.	Percentage composition by volume of the gas.							Percentage composition by weight of the solid residue.									
			Carbonic anhydride.	Carbonic oxide.	Nitrogen.	Sulphhydric acid.	Marsh-gas.	Hydrogen.	Oxygen.	Potassium carbonate.	Potassium sulphate.	Potassium hyposulphite.	Potassium monosulphide.	Potassium sulphocyanate.	Potassium nitrate.	Potassium oxide.	Ammonium sesquicarbonate.	Sulphur.	Charcoal.
Pebble, W.A.	Means		48·92	13·70	32·13	2·60	0·31	2·34	...	57·19	12·47	13·89	10·25	0·27	0·23	...	0·10	5·45	0·15
	Highest		51·75	16·09	32·75	4·23	0·68	3·50	...	64·20	15·02	32·18	19·12	0·57	0·48	...	0·17	8·45	1·35†
	Lowest		44·78	10·87	31·31	1·70	...	1·67	...	50·20	9·13	3·71	2·23	0·06	...	...	0·06	0·61	Trace
R.L.G., W.A.	Means		49·29	12·47	32·91	2·65	0·43	2·19	0·06	59·06	14·59	13·20	6·27	0·22	0·26	...	0·07	6·26	0·07
	Highest		52·65	17·04	35·60	4·29	0·84	3·01	0·57	66·51	24·22	25·33	9·92	0·49	0·56	...	0·18	12·03	0·71
	Lowest		46·29	8·98	30·29	1·56	...	1·27	...	48·68	4·64	3·08	2·02	0·05	...	...	0·04	1·25	Trace
F. G., W. A.	Means		50·63	10·46	33·20	2·48	0·19	2·96	0·08	48·32	21·11	24·79	2·41	0·12	0·16	1·29	0·05	1·75	...
	Highest		53·34	16·25	34·64	3·76	0·50	4·13	0·28	59·39	24·22	34·61	5·12	0·25	0·26	5·39	0·15	5·72	...
	Lowest		44·76	7·71	32·22	2·00	...	2·04	...	41·88	17·86	5·30	...	0·02	0·08	...	0·01	0·09	...
96. R.L.G., W.A.		60 %	46·29	14·52	32·40	4·29	0·36	2·14	...	65·27	10·71	6·89	7·65	0·28	0·45	...	0·09	8·66	...
78. R.F.G., W.A.		70 ,,	52·40	8·86	34·51	1·60	0·12	2·51	...	58·94	21·89	8·15	4·22	0·04	0·06	...	0·06	6·65	Trace
79. Spanish spherical		70 ,,	53·34	4·62	37·80	2·74	...	1·29	0·21	34·97	47·62	7·60	3·17	0·04	0·93	...	0·04	5·63	...
196. Curtis and Harvey's No. 6		30 ,,	50·22	7·52	34·46	2·08	2·46	3·26	...	58·51	21·43	3·93	10·02	...	0·29	...	0·09	5·73	...
194. Mining powder		30 ,,	32·15	33·75	19·03	7·10	2·73	5·24	...	40·78	0·58	5·84	33·20	2·92	0·09	...	1·76	12·93	2·00

* See Table 12.

† Not estimated—insoluble residue chiefly iron pyrites.

Table 2.*—*Composition by weight of the products of combustion of* 1 *gramme of*

No. of experiments.	Nature of powder.	Mean density of products of combustion.	Proportions by weight of gaseous products.							
			Carbonic anhydride.	Carbonic oxide.	Nitrogen.	Sulphhydric acid.	Marsh-gas.	Hydrogen.	Oxygen.	Potassium carbonate.
8	Pebble, W. A. .	10	·2553	·0514	·1140	·0133	...	·0007	...	·3084
7		20	·2494	·0570	·1108	·0182	...	·0009	...	·3186
9		30	·2595	·0545	·1113	·0124	...	·0007	...	·3282
12		40	·2624	·0471	·1085	·0069	·0006	·0006	...	·3115
14		50	·2743	·0469	·1128	·0083	·0012	·0005	...	·3069
37		60	·2654	·0470	·1087	·0093	·0011	·0005	...	·3213
38		70	·2604	·0415	·1065	·0128	·0007	·0005	...	·2852
43		80	·2690	·0396	·1084	·0080	·0006	·0004	...	·3322
77		90	·2684	·0359	·1080	·0085	·0013	·0005	...	·3645
		Means	·2627	·0468	·1099	·0109	·0006	·0006	...	·3196
		Highest	·2743	·0570	·1140	·0182	·0013	·0009	...	·3645
		Lowest	·2494	·0359	·1065	·0069	...	·0004	...	·2852
1	R. L. G., W. A.	10	·2569	·0300	·1188	·0164	·0006	·0005	...	·2972
3		20	·2477	·0389	·1189	·0148	·0001	·0006	·0022	·3094
4		30	·2582	·0386	·1096	·0126	...	·0007	...	·2984
11		40	·2595	·0356	·1125	·0077	·0005	·0006	...	·2789
70		50	·2494	·0558	·1011	·0065	·0016	·0007	...	·3482
39		60	·2648	·0467	·1065	·0066	·0007	·0005	...	·3597
96		60	·2457	·0490	·1090	·0176	·0007	·0005	...	·3702
41		70	·2576	·0441	·1053	·0114	·0011	·0004	...	·3435
44		80	·2672	·0401	·1060	·0062	·0014	·0004	...	·3777
68		90	·2720	·0352	·1074	·0076	·0015	·0003	...	·3715
		Means	·2580	·0414	·1095	·0106	·0008	·0005	·0002	·3355
		Highest	·2720	·0558	·1189	·0176	·0016	·0007	·0022	·3777
		Lowest	·2457	·0300	·1011	·0062	...	·0003	...	·2789
16	F. G., W. A. .	10	·2423	·0561	·1122	·0095	·0004	·0010	·0006	·2772
17		20	·2475	·0410	·1074	·0153	...	·0010	...	·3401
18		30	·2586	·0370	·1050	·0088	...	·0008	·0010	·2645
19		40	·2639	·0334	·1055	·0079	...	·0008	...	·2576
75		50	·2611	·0338	·1080	·0087	·0005	·0007	...	·3207
40		60	·2651	·0312	·1080	·0089	·0003	·0006	...	·2391
42		70	·2678	·0253	·1100	·0080	·0009	·0005	·0006	·2461
47		80	·2598	·0265	·1105	·0101	·0008	·0005	·0007	·2514
69		90	·2698	·0247	·1088	·0116	·0003	·0005	...	·2880
		Means	·2596	·0343	·1084	·0099	·0003	·0007	·0003	·2762
		Highest	·2698	·0561	·1122	·0153	·0009	·0010	·0010	·3401
		Lowest	·2423	·0247	·1050	·0079	...	·0005	...	·2391
78	R. F. G., W. A.	70	·2652	·0285	·1110	·0063	·0002	·0006	...	·3420
79	Spanish spherical	70	·2424	·0133	·1091	·0096	...	·0003	·0007	·2161
196	Curtis and Harvey's No. 6 .	30	·2576	·0245	·1124	·0082	·0046	·0008	...	·3395
194	Mining powder .	30	·2254	·1508	·0849	·0385	·0070	·0017	...	·1938

* See Table 13.

fired gunpowder of the undermentioned natures, and of various gravimetric densities.

Proportions by weight of the solid residue.									Water.	Proportion by weight of total gaseous products.	Proportion by weight of total solid products.	Water.
Potassium sulphate.	Potassium hyposulphite.	Potassium monosulphide.	Potassium sulphocyanate.	Potassium nitrate.	Potassium oxide.	Ammonium sesquicarbonate.	Sulphur.	Charcoal.				
·0835	·1152	·0412	·0005	·0027	...	·0009	·0034	...	·0095	·4347	·5558	·0095
·0760	·0206	·1001	·0003	...	...	·0005	·0381	...	·0095	·4363	·5542	·0095
·0696	·0239	·0911	·0012	·0002	...	·0007	·0372	...	·0095	·4384	·5521	·0095
·0745	·0794	·0548	·0014	·0005	·0077	·0004	·0342	...	·0095	·4261	·5644	·0095
·0652	·0335	·1045	·0013	·0011	...	·0003	·0337	...	·0095	·4440	·5565	·0095
·0752	·0556	·0641	·0019	·0017	...	·0003	·0384	...	·0095	·4320	·5585	·0095
·0726	·1827	·0127	·0022	·0014	...	·0003	·0110	...	·0095	·4224	·5681	·0095
·0584	·1167	·0220	·0026	·0018	...	·0005	·0303	...	·0095	·4260	·5645	·0095
·0518	·0754	·0218	·0032	·0025	...	·0007	·0480	...	·0095	·4226	·5679	·0095
·0696	·0781	·0569	·0016	·0013	·0009	·0005	·0306	...	·0095	·4314	·5601	·0095
·0835	·1827	·1045	·0032	·0027	·0077	·0009	·0480	...	·0095	·4440	·5681	·0095
·0518	·0206	·0127	·0003	·0002	...	·0003	·0034	...	·0095	·4224	·5521	·0095
·1160	·1154	·0228	...	·0032	...	·0003	·0041	·0072	·0106	·4232	·5662	·0106
·1364	·0326	·0541	·0003	·0007	...	·0004	·0323	·0001	·0106	·4232	·5662	·0106
·1380	·0732	·0334	·0003	·0002	...	·0002	·0260	...	·0106	·4197	·5697	·0106
·1310	·1379	·0116	·0009	·0007	...	·0002	·0118	...	·0106	·4164	·5730	·0106
·0266	·1455	·0204	·0017	·0029	...	·0006	·0284	...	·0106	·4151	·5743	·0106
·0619	·0365	·0559	·0015	...	...	·0006	·0475	...	·0106	·4258	·5636	·0106
·0608	·0392	·0434	·0016	·0026	...	...	·0491	...	·0106	·4225	·5669	·0106
·0600	·1059	·0219	·0028	·0024	...	·0001	·0329	...	·0106	·4199	·5695	·0106
·0501	·0175	·0514	·0014	·0010	...	·0006	·0684	...	·0106	·4213	·5681	·0106
·0482	·0486	·0409	·0021	·0011	...	·0009	·0521	...	·0106	·4240	·5654	·0106
·0829	·0752	·0356	·0013	·0015	...	·0004	·0353	·0007	·0106	·4211	·5683	·0106
·1380	·1455	·0559	·0028	·0032	...	·0009	·0684	·0072	·0106	·4258	·5743	·0106
·0266	·0175	·0116	...	...	...	...	·0041	...	·0106	·4151	·5636	·0106
·1005	·1338	·0193	...	·0011	·0308	·0004	...	...	·0148	·4221	·5631	·0148
·1388	·0304	·0294	·0001	·0005	...	·0009	·0328	...	·0148	·4122	·5730	·0148
·1302	·1583	·0161	·0004	·0006	...	·0001	·0038	...	·0148	·4112	·5740	·0148
·1250	·1640	·0193	·0004	·0005	...	·0002	·0067	...	·0148	·4115	·5737	·0148
·1186	·0768	·0248	·0004	·0005	...	·0005	·0301	...	·0148	·4128	·5724	·0148
·1269	·1822	...	·0009	·0010	·0183	·0001	·0026	...	·0148	·4141	·5711	·0148
·1202	·1836	...	·0013	·0011	·0170	·0002	·0026	...	...	·4131	·5721	·0148
·1218	·1995	...	·0014	·0015	...	·0002	·0005	...	·0148	·4089	·5763	·0148
·1046	·1474	·0152	·0014	·0015	...	·0002	·0112	...	...	·4157	·5695	·0148
·1207	·1418	·0138	·0007	·0009	·0074	·0003	·0100	...	·0148	·4135	·5717	·0148
·1388	·1995	·0294	·0014	·0015	·0308	·0009	·0328	...	·0148	·4221	·5763	·0148
·1005	·0304	...	...	·0005	...	·0001	...	...	...	·4089	·5631	·0148
·1268	·0472	·0245	·0002	·0004	...	·0005	·0386	...	·0080	·4118	·5802	·0080
·2943	·0470	·0196	·0003	·0058	...	·0002	·0348	...	·0065	·3754	·6181	·0065
·1243	·0228	·0582	...	·0017	...	·0005	·0332	...	·0117	·4081	·5802	·0117
·0028	·0277	·1578	·0138	·0004	...	·0084	·0614	·0095	·0161	·5083	·4756	·0161

regards as satisfactorily explaining ("and definitely reducing to five simple reactions") the formation of carbon dioxide, carbon monoxide, potassium sulphate, sulphide and carbonate, from a powder of what we call normal composition.*

After giving further equations which apply to the extreme results (in regard to the chief products only) assumed to be obtainable from the introduction, on the one hand, of excess of saltpetre, on the other of excess of charcoal, into the composition of powder, M. Berthelot passes to what he terms the accessory products and, excluding from these potassium hyposulphite, which he deals with separately, he first gives two equations to account for the production of sulphocyanide; then two more to explain the existence of ammonium sesquicarbonate (which he believes to be formed by the action of water-vapour on potassium cyanide). The existence of sulphuretted or free hydrogen are explained by two more equations, and marsh-gas is assumed to result from "the pyrogenous decomposition of the charcoal in the powder." Lastly, an equation is given to account for the possible formation of traces of hyposulphite, which Berthelot however regards

* The five simple reactions in question are thus explained :—

1. $NO_6K+S+C_3 = K.S.+3CO_2+N$
2. $NO_6K+S+C_3 = K.C.O_3+CO.+CO_2+N+S$
3. $NO_6K+S+C_3 = KCO_3+1\frac{1}{2}C.O._2+N+S+\frac{1}{2}C$
4. $NO_6K+S+C_3 = KSO_4+2CO.+N+C$
5. $NO_6K+S+C_3 = KSO_4+CO._2+N+C_2$

When sulphate is formed in such small quantities that it may be neglected, the simultaneous reactions supposed to occur are 1, 2, and 3, by quantities of the powder proportionate to the numbers $\frac{1}{3}$, $\frac{1}{2}$, and $\frac{1}{6}$; but when the sulphate amounts to 12 or 14 per cent., the simultaneous reactions supposed to occur are Nos. 1, 3, 4, and 5, with quantities of powder corresponding to the numbers $\frac{1}{3}$, about $\frac{1}{2}$, $\frac{1}{8}$, and $\frac{1}{12}$. As there is only one single instance out of twenty-nine analyses of powder-residues in which the sulphate was found to amount to as little as 4·6 per cent. of the solid products (the next lowest proportion being nearly double that amount), it can scarcely be assumed that M. Berthelot's first arrangement of reactions can represent any but a most exceptional result. Again, the acceptance of his arrangement of four equations in the proportions he indicates as accounting for the formation of the chief products when the sulphate amounts to 12 or 14 per cent. of the total constituents, involves the assumption that a somewhat considerable proportion of charcoal should remain unoxidised; in fact, nearly 2·5 per cent. of carbon should be found in the residue. The detection and determination of such a constituent of powder-residue does not involve any difficulty, yet there were only three instances out of eighteen residues (in which the sulphate was considerable in amount) where the charcoal was present in estimable quantities; in two of these it was below 1 per cent., in the other it was only 0·01 per cent. In a few other residues only traces of charcoal were discovered; the larger number contained none.

These points are referred to in illustration of how imperfectly M. Berthelot's not very simple arrangement of theoretical reactions correspond to the results actually obtained, even so far only as the chief products are concerned.

entirely as a product formed during the collection and analytical treatment of the solid residue, but which we nevertheless believe we shall conclusively prove * to be formed in very notable quantities before the solid residue can have undergone alteration from external causes.

It will be seen from the foregoing outline of M. Berthelot's theoretical explanation of the chemical changes involved in the metamorphosis of gunpowder, that the simplest form of expression which he can give to the formation of the products of explosion consists in the incorporation of nine or ten distinct reactions occurring simultaneously, but in very variable proportions, which have to be supplemented by three or four other chemical equations, by which the formation, during the process of cooling, of certain products believed to be secondary, is explained. Now, although such speculations as the above are unquestionably interesting, and, it may be added, of a nature which must occur to those who desire to give some kind of definite explanation, for purposes of elementary instruction, of the chemical changes involved in the explosion of powder, we fail to see that beyond this they do more than afford the strongest confirmation of the correctness of our conclusion, that "no value whatever can be attached to any attempt to give a general chemical expression to the metamorphosis of a gunpowder of normal composition."

With regard to the *potassium hyposulphite* which is included in our statement of the composition of the solid products of explosion, we have to submit the following considerations.

In the analytical results furnished by the solid residues, as detailed in our first memoir, the hyposulphite ranged in amount from 3 to 35 per cent.; and on comparing the results of different analyses it is observed that in most instances the proportion of monosulphide was small when the hyposulphite was large in amount, and in a few instances—all of them F. G. powder-residues—in which the proportion of the latter was very high, there was no sulphide at all.

Being fully alive to the possibility of the existence of potassium polysulphide in the solid residue giving rise to the production of some hyposulphite through the agency of atmospheric oxygen, great precautions were taken, especially in the latter experiments, in collecting and preserving the residue and in submitting it to treatment for analysis, to guard against this possible source of error.

In the first place, it should be mentioned that the residue consisted in nearly all cases of fused, very hard masses, collected at the

* See note at end of this memoir (p. 309).

bottom of the explosion-vessel, the sides of which were, moreover, generally covered with very thin films. The action of atmospheric oxygen upon the fused solid could only be superficial, but would vary in extent with the amount of surface of the residue exposed to the air during removal from the explosion apparatus or subsequent exposure. The latter was avoided as much as possible, as the residues were transferred at once, as they were detached from the surfaces of the explosion-vessel, into small bottles, in which they were carefully sealed up. It was only in one or two instances that, before opening the bottles, an odour of sulphuretted hydrogen, distinctly perceptible at the sealed surfaces of the mouths, indicated a slight imperfection in the sealing of the bottles.

The difficulties in the way of reducing to a minimum the exposure to air of the residues during their detachment from the explosion-vessel were, however, very much greater. We pointed out in our first memoir that in almost all cases the residues were in the form of exceedingly hard and compact masses, which had to be cut out with steel chisels, and that although portions of the mass were detached in the form of lumps, a considerable amount of it flew off before the chisel in fine dust. The utmost care was taken to avoid exposure of the detached residues to the air, but it was of course impossible to avoid their being more or less attacked by atmospheric oxygen during the period of their collection. There is no doubt, moreover, that the residues, which differed greatly from each other in structure and in their tendency to absorb moisture and to become heated upon exposure to air, were susceptible in very variable degree to atmospheric oxidation. We, therefore, are quite prepared to admit that, of the large amount of hyposulphite found in a number of the analyses, a proportion, and in some instances possibly a large one, may have been produced by the agency of atmospheric oxygen during the removal of the residue from the apparatus; and the results of some special experiments, which we shall presently quote, appear to favour the conclusion that in those instances where no sulphide was discovered, its absence may have been ascribable to atmospheric oxidation. We regret having neglected to make any reference to this probable source of error in describing the results of our analyses, our belief being at the time that any important alteration of the residue by atmospheric action was sufficiently guarded against; at the same time, it is right we should point out that, in several instances in which the circumstances attending the manipulation of the solid residue and its consequent mechanical

condition were apparently most favourable to its accidental oxidation, the proportion of hyposulphite formed was comparatively moderate in amount.

On the other hand, we cannot concur in M. Berthelot's view that the existence of hyposulphite among our analytical results is also ascribable in part to accidental oxidation of potassium sulphide during the analytical manipulations. These were carried out with great uniformity so far as certain preliminary operations were concerned, which consisted, firstly, in dissolving the residue in water which had been carefully boiled to expel air, and secondly, in filtering the solution in closed vessels—both of these being rapidly completed operations. The receiving vessel contained pure ignited cupric oxide, with which, as soon as the filtering operation was completed, the solution was agitated until it became colourless.

The fact that in some of the analyses, all of which, we repeat, were uniformly conducted in regard to the above points, from 3 to 10 per cent. only of hyposulphite were found, while the proportion of monosulphide in these analyses ranged from 7 to 19 per cent. (being above 9 per cent. in eight instances), appears to afford substantial proof that accidental atmospheric oxidation during the collection and analysis of the residues is not sufficient to account for all but the very small quantities of hyposulphite which M. Berthelot considers could only have pre-existed in the residue examined by us. That chemist appears, moreover, to have overlooked the following facts given by us in our first memoir:—

1. Separate examinations (conducted precisely alike) of the upper and lower portions of some of the residues showed that considerably larger proportions of hyposulphite existed in the *upper* portions. In one case quoted by us in our first memoir, the upper portion contained 17·14 per cent. of hyposulphite, while the lower portion only contained 4·34 per cent. At the same time there was only a difference of 1·27 per cent. in the proportions of monosulphide existing in the two portions of the residue (6·03 in the upper part, and 7·3 in the lower), while there was a very great difference in the amount of free sulphur (4·88 in the upper part, and 10·09 in the lower).

2. One of the small buttons of the fired solid products, of which there was generally one found attached to the firing plug in the cylinder, was examined for sulphide and hyposulphite (it having

been detached without fracture, and at once sealed up in a small tube). It contained the latter, but none of the former, while the mass of the residue of this particular experiment contained a somewhat considerable proportion of sulphide.

3. The production of high proportions of hyposulphite was but little affected by any variations in the circumstances attending the several explosions (*i.e.*, whether the spaces in which the powder was exploded were great or small), excepting that the amount was high in all three cases when the powder was exploded in the largest space. On the other hand, a great reduction in the size of grain of the gunpowder used appeared to have a great influence upon the production of hyposulphite, as when passing from a very large-grain powder (pebble or R. L. G.) to a fine grain-powder (F. G.).

Thus the production of hyposulphite exceeded 20 per cent. in—

3	experiments out of	9	with	pebble-powder	(Nos. 8, 38, 43).	(pp. 211, [etc.)
3	,, ,,	10	,,	R. L. G. ,,	(Nos. 1, 11, 70).	
7	,, ,,	9	,,	F. G. ,,	(Nos. 16, 18, 19, 40, 42, 47, 69).	

It was below 10 per cent. in—

4	experiments out of	9	with	pebble-powder	(Nos. 7, 9, 11, 37).
5	,, ,,	10	,,	R. L. G. ,,	(Nos. 3, 39, 44, 68, 96).
1	,, ,,	9	,,	F. G. ,,	(No. 17).

There were no circumstances connected with the carrying out of the explosions, or with the collection and analysis of the residues, to which the above great differences between the results furnished by fine-grain powder and by the two large grain powders could be ascribed.

While, however, certain of the great variations in the proportions of hyposulphite and sulphide, which cannot be accounted for by variations of structure of the residue or of manipulations favourable to oxidation by atmospheric agency, appear to us to demonstrate that the hyposulphite is formed in the solid residue before the explosion-vessel is opened, and indeed in such amount that it must be regarded as an important product (whether it be a primary or a secondary one), we have been anxious to obtain, if possible, some more decisive evidence as to the probable proportions of hyposulphite actually existing in the residues furnished by the explosion of gunpowder in closed vessels. We therefore varied the method of

collecting and preparing the residues for analysis, in the experiments of which the following is an account:—

1. 5960 grains (386·2 grms.) of the R. L. G. and pebble powders used in these researches were fired in the large cylinder under a density of 0·40.

Immediately on opening the cylinder in each case, the solid products were as nearly as possible divided into two equal portions, consisting of the top and the bottom. Each of these portions was again divided roughly into two equal parts, one of which, in large lumps, was, as rapidly as possible (being but for a few seconds exposed to the air), sealed in dry bottles freed, or nearly so, from oxygen, the other moieties being finely ground and freely exposed to the air for 48 hours.

The only point of difference calling for remark in the appearance of the two residues was the difference in colour, the residue from the pebble being decidedly the lighter in colour, both on the surface and in fracture; but there were material differences in the behaviour of the *ground* portions of the two powder-residues.

With both powders, the bottom ground portion heated very decidedly more than the top; but while, in the R. L. G., this tendency was exhibited in a remarkably low degree, with the pebble the tendency to heat was, we think, abnormally high. In the latter case, the ground deposit from the top began to heat immediately on being placed upon paper. The deposit on the apex of the cone and in the interior, where the heat was highest, changed rapidly in colour to a light yellow, tinged with green.

The ground bottom part of the residue darkened considerably during the development of heat, and an orange-coloured deposit was condensed on the surface.

When the heat was highest, a considerable quantity of vapour was given off. Its smell was very peculiar; SH_2 was distinctly perceptible, but was by no means the dominant odour.

The maximum temperature appeared to be reached at about twenty minutes after exposure. A thermometer placed in the centre indicated a temperature of over 600° Fahr. (315° Cent.), and the paper on which the residue was placed was burnt through. After half an hour's exposure the deposit cooled very rapidly.

It should be observed that the physical characteristics of the ground deposit were altered very materially by the heating. When the residue is taken out of the exploding cylinder, it is difficult to pound in the mortar, being somewhat unctuous; but

after the development of heat it becomes crisp, and is readily powdered.

2. In the examination that we have instituted of the products of explosion of a sample of sporting powder (Curtis and Harvey's No. 6), and of mining powder, the following course of proceeding was adopted for the removal of the solid residue from the explosion-vessel, and its preparation for analysis:—Distilled water which had been freed from air by long-continued boiling, was siphoned into the explosion-vessel when the latter had cooled, so that air was never allowed to come into contact with the solid residue. When the cylinder was thus quite filled with water, it was closed, and set aside for sufficient time to allow the residue to dissolve completely. The solution was then decanted into bottles freed from oxygen, which were quite filled with the liquid, and carefully sealed up until required for analysis, in carrying out which the course already described was pursued.

The products obtained by the first of these modifications of the ordinary course of procedure were submitted to partial examination, the chief object being to see to what extent the proportions of hyposulphite and sulphide varied in the upper and lower portions of the residue, and the extent to which they were affected by the great difference in the mode of treatment sustained by the different portions of one and the same residue. The proportion of hyposulphite was determined in every instance, and the products were also examined in all cases for sulphide. In the first experiment the exact proportion of this latter constituent was ascertained only in one of the three portions of the residue in which it existed; it will be seen that one of the ground portions contained none. The sulphate was determined in all instances, and, in the second experiment, the proportions of carbonate existing in the upper and lower portions of the (unground) residue were ascertained. The analytical results obtained are given in the following table:—

TABLE 3.—*Illustrating the effects of exposure upon the proportions of hyposulphite and monosulphide in the solid products.*

Description of experiment.			Percentage composition by weight of solid residue.				
			Potassium sulphate.	Potassium hyposulphite.	Potassium monosulphide.	Sulphur.	
Experiment No. 121.							
R. L. G. powder, Waltham-Abbey make. Proportion of space occupied by the charge in the chamber, about 40 per cent.	Top portion of residue	Unground	12·14	5·83	Large quantity	not determined	...
		Ground	11·52	27·52	none	...	...
	Bottom portion of residue	Unground	10·85	8·51	19·76	5·0	...
		Ground	10·87	36·34	under 3 per cent.	...	...
Experiment No. 122.							
Pebble-powder, Waltham-Abbey make. Proportion of space occupied by the charge in the chamber, about 40 per cent.	Top portion of residue	Unground	14·08	5·01	13·26	8·71	Carbonate of potassium 58·9
		Ground	16·22	31·06	none	...	...
	Bottom portion of residue	Unground	13·80	6·46	16·12	7·49	Carbonate of potassium 56·06
		Ground	16·62	32·91	none	...	...

It will be seen from the foregoing numerical results that in both experiments those portions of the residue which were exposed to the air only for a few seconds, and of which only small surfaces *were* thus exposed (as they were collected in large lumps), contained hyposulphite ranging in amount from 5 to 8·5 per cent. Those portions which were specially treated for the purpose of favouring to the utmost the formation of hyposulphite from sulphide through atmospheric agency, contained, as was to be expected, very large proportions of the former, while the latter had entirely disappeared in three out of the four portions of very finely pulverised residue. In the fourth, however, even after its free exposure to air for forty-eight hours, there still remained nearly 3 per cent. of sulphide. Now, as in no single instance in the entire series of our experiments did any accidental circumstances occur which even distantly approached the special conditions favourable to the oxidation of the sulphide which were introduced into these particular experiments, we consider ourselves justified in arriving at the conclusion that the total absence of sulphide in the residues furnished by the fine-grain powder in Experiments 40, 42, and 47 was not due to accident in the manipulations, and that in those residues in our series of analyses which were found to contain large quantities of hyposulphite (as in six out of the nineteen experiments with pebble and R. L. G. powder, and eight out of the nine with F. G. powder), a great proportion, at anyrate, of that hyposulphite existed in those particular residues before their removal from the explosion-vessel. The circumstance that the residues furnished by our two most recent experiments (with sporting powder and mining powder), in the treatment of which the possibility of accidental formation of hyposulphite was altogether guarded against, contained 4, and about 6, per cent. of hyposulphite, demonstrates that even under these conditions a very notable quantity of that substance is found in powder-residue; but it cannot, we consider, be taken to support the view that, in a residue containing a much higher proportion of hyposulphite, the existence of the whole or a large part of that excess is ascribable to accident of manipulation. In the series of experiments with pebble-powder there were three, in that with R. L. G. powder four, while in that with F. G. powder there was one, of which the residues contained proportions closely similar to those furnished by the two experiments above quoted, there being no peculiarity in those seven experiments nor any attendant circumstances which could be assigned as a possible reason why the proportions of hyposulphite in those cases should be so much

lower than in the other experiments with the same powders, carried out under the same conditions. We therefore cannot but conclude that the production of a small or of a large proportion of hyposulphite (whether as a primary or secondary product, *but before the explosion-vessel is opened*) is determined by some slight modification of the conditions attending the explosion itself.

From an examination of the proportions of potassium sulphate found in the different parts of the two residues, it will be seen that in the case of the R. L. G. there was a variation of only 1·27 per cent. in the sulphate in different parts of the residue, and that in the top and bottom portions the amounts found in the unground and ground parts were almost identical, so that the proportion of sulphate was in no way affected by the prolonged exposure of the finely-ground residue to air. In the pebble-powder experiment the sulphate varied in the different parts to the extent of 2·82 per cent., and the higher proportions happened to exist in the ground parts of this residue; but the differences can scarcely be considered sufficiently important to ascribe them to any other cause than a little variation in the composition of different parts of this residue.

Some of the later of our experiments with R. L. G. powder given in the first memoir furnished products which, when calculated upon the results of analysis made at the commencement of these researches, of a sample of the powder taken from the upper part of the contents of the barrel, presented greater discrepancies in some points than was the case with some of the earlier products. It was, therefore, considered desirable to repeat the analysis of this powder, operating upon a sample taken from the *lower* part of the barrel. The results of the two analyses are as follows:—

Components, per cent.	R. L. G. powder. From upper part of barrel.		R. L. G. powder. From lower part of barrel.	
Saltpetre		74·95		74·430
Potassium sulphate		0·15		0·133
Sulphur		10·27		10·093
Charcoal: Carbon	10·86	13·52	12·398	14·286
Charcoal: Hydrogen	0·42		0·401	
Charcoal: Oxygen	1·99		1·272	
Charcoal: Ash, etc.	0·25		0·215	
Water		1·11		1·058

The foregoing numbers, which are in each case the means of two very concordant analyses, present sufficient differences to establish a small but decided variation in the composition of this powder, of which, be it remembered, very considerable quantities were employed in the course of the series of experiments. It appeared to us, therefore, that we were warranted in calculating the earlier results obtained with this powder (produced in 10 to 40 per cent. space) upon the composition as represented by the first analysis, and in recalculating the later ones furnished by the lower part of the contents of the barrel upon the analysis of the sample taken from that part of the powder.

In completing these researches, it appeared to us of interest to include two other descriptions of gunpowder in our series of experiments, one of them a representative of the sporting powder class, the other representing the higher qualities of blasting or mining powder, which are well known to differ very materially in composition from the powders used for military purposes. The composition of these two samples of powder, which were obtained from Messrs Curtis and Harvey, is given in the following tabular statement:—

Components, per cent.		Sporting powder. Curtis and Harvey's No. 6.		Mining powder.	
Saltpetre		74·40		61·66	
Potassium	Sulphate	0·29		0·12	
	Chloride	Trace.		0·14	
Sulphur		10·37		15·06	
Charcoal	Carbon	10·66	13·78	17·93	21·41
	Hydrogen	0·52		0·66	
	Oxygen	2·29		2·23	
	Ash	0·31		0·59	
Water		1·17		1·61	

It will be seen that the sporting powder did not differ very widely in composition from the several military powders of Waltham-Abbey manufacture, while the mining powder presents very important differences from any of the other powders experimented with by us, as well as from those used by recent foreign experimenters, to which we have referred in our first memoir.* The proportion of saltpetre is about 11·3 per cent. lower than in the military powders, while the proportions of charcoal and sulphur are each higher by about one-half. The percentage composition of the charcoal contained in these two powders is given below, and a comparison of the

* *Phil. Trans.*, 1875, part i., p. 72.

numbers with those furnished by analysis of the charcoal from the several military powders shows that the sporting powder charcoal is intermediate between the R. F. G. and F. G. charcoal, and that the mining powder charcoal resembles that contained in the pebble-powder. Both these charcoals contained, however, a decidedly higher proportion of mineral constituents than the charcoal manufactured at Waltham Abbey.

Percentage composition of the charcoals contained in the several descriptions of gunpowder employed.

	Pebble.	R. L. G.	R. F. G.	F. G.	Curtis and Harvey.		Spanish.
					Sporting.	Mining.	
Carbon . . .	85·26	80·32	75·72	77·88	77·36	83·74	76·29
Hydrogen . .	2·98	3·08	3·70	3·37	3·77	3·07	3·31
Oxygen . . .	10·16	14·75	18·84	17·60	16·62	10·45	14·87
Ash	1·60	1·85	1·74	1·15	2·25	2·74	5·53

The results obtained by firing these two gunpowders in 30 per cent. space are included in the statements given in Tables 1 and 2.*

It will be remembered that a special method of collecting for analysis the solid products furnished by these powders was adopted, with the object of altogether guarding against the possibility of accidental conversion of sulphide into hyposulphite. The analytical results show that the chief differences between the results of explosion of the sporting powder (in 30 per cent. space) and of the R. F. G. powder (in 70 per cent. space) consisted, as regards the gaseous products, in the slightly higher proportion of carbonic anhydride, and in the very decidedly larger amount of marsh-gas furnished by the former, and, as regards the solid products, in the higher proportion of sulphide and lower proportion of hyposulphite; the quantities of these constituents of the residue are very similar to those found in the R. L. G. residue exploded in 80 per cent. space.

The gaseous and solid products of explosion of the mining powder differed very greatly, as was anticipated, from those furnished by all the other powders, as regards their proportions. The carbonic oxide was double the highest amount furnished by any of the other powders, while the carbonic anhydride, which in the three series of experiments ranged from 45 to 53 per cent. of the total volume of the gases, amounted only to 32 per cent., the two gases existing in

* See also Tables 12 and 13.

about equal proportions. Marsh-gas and hydrogen were present in unusually high proportions, and the sulphuretted hydrogen amounted to 7 per cent., being nearly double the highest proportion found in all the other experiments. The solid residue presented very interesting points of difference. The potassium carbonate was, as might have been anticipated, comparatively small in amount (though some of the experiments with F. G. powder gave similar results in this respect), but there was only 0·5 per cent. of sulphate formed, while the monosulphide amounted to 33 per cent. of the solid residue, and the free sulphur to nearly 13 per cent. Federow's experiments are the only ones in which so high a (and indeed a somewhat higher) percentage of sulphide is recorded, and among the several experiments with R. L. G. powder, in which only small proportions of sulphate were formed, there was only one residue in which the free sulphur was as high in amount as that formed in the mining powder residue. It will be seen that the hyposulphite amounted to nearly 6 per cent.: 2 per cent. more than was furnished by the sporting powder under *precisely* similar conditions of experiment, and *double* the smallest amount formed in any of the series of experiments, conducted without the very special precautions which were applied in dealing with the residue of the powder under discussion. The ammonium sesquicarbonate was considerably higher in amount than in any other experiments (though still much below the amounts found by Karolyi and Linck), and the potassium sulphocyanide amounted to 3 per cent., or about five times the amount found in any other experiments excepting that of Linck.

Lastly, there was a much more considerable amount of charcoal in this experiment than in any other.

It need scarcely be stated that the very distinctive difference between the composition of the solid and gaseous products of this powder are, generally, such as would have been predicted from the comparatively small proportion borne by the oxidising agent to the oxidisable constituents in the mining powder.

It will be seen presently that the experiments with mining powder presented other features of great interest in addition to those elicited by the chemical examination of the products of explosion. In concluding our observations on these, we should point out that fresh confirmation is afforded by this experiment of the fact insisted upon by us, namely, that hyposulphite must be classed among the invariable * products of explosion of gunpowder in closed spaces.

* See note at end of this paper (p. 309).

An examination of the three complete series of results obtained by the explosion of pebble, R. L. G., and F. G. powders in closed spaces in which their gravimetric densities varied from 0·1 to 0·9 per cent. of the space, and which are given in detail in Tables 1 and 2,* suggests the following observations additional to those included in our first memoir, on the nature and relations to each other of the *solid* products furnished by the several powders.

Comparing the highest, lowest, and mean proportions of the chief solid products furnished by the three powders, which differed but little in composition from each other, the following points are observed:—

1. The proportions of *potassium carbonate* furnished by R. L. G. and by P. powder are very similar, while the highest, lowest, and mean results furnished by F. G. are all decidedly lower than those from the other two powders.

2. The mean proportions of *sulphate* furnished by P. and R. L. G. are not far different, though the highest amount furnished by the *former* is considerably below, and the lowest number considerably above, the corresponding numbers furnished by R. L. G. powder. But the mean and the lowest proportions of *sulphate* furnished by F. G. is very considerably higher than the corresponding numbers obtained with the two other powders (the *highest* amounts obtained with F. G. and R. L. G. being identical).

The generally greater extent to which the sulphur has undergone *complete* oxidation in the case of the F. G. powder is certainly not a result which can be in the least ascribable to accidental circumstances attending the experiments, and the fact that it corresponds with the generally higher proportions of hyposulphite furnished by this powder affords additional support to the view which we maintain, that the production of the latter substance, in variable, and sometimes very considerable amounts from the powders experimented with, is not to be explained away by ascribing it to accident of manipulation.

3. It will be seen that, whereas the means of the amounts of hyposulphite obtained in the analyses of the residues from pebble and R. L. G. powders are almost identical, they amount to little more than half that of the mean numbers furnished by the analyses of the F. G. residues. But the highest result furnished by pebble-powder is nearly equal to, and that furnished by R. L. G. powder is not far below, the highest number obtained with F. G. powder.

* See also Tables 12 and 13.

4. As regards potassium monosulphide, the mean result in the case of pebble is very considerably higher than that furnished by R. L. G. powder, and more than four times the mean result given by F. G. powder. It is noteworthy, too, as indicative of the great and apparently uncontrollable irregularity in the amount of this product formed by the explosion of powders of normal composition in closed spaces, that the proportions of sulphide produced from pebble-powder at the higher pressures were very small, and similar to those formed from F. G. powder at low as well as high pressures (except where none was found in the residues), and that in several instances very considerable quantities were formed from pebble at densities ranging from 20 to 60 per cent., some of them being indeed very much higher than that produced in the special experiment with sporting powder, in which extra precautions were adopted to guard against oxidation of sulphide. Then in the case of R. L. G. powder, the proportions of sulphide found may be said to be intermediate between those produced from pebble and F. G., the amounts ranging from 2 to 10 per cent.; and the higher and lower proportions are indiscriminately distributed through the different residues obtained at low, high, and intermediate pressures. In no instance, either with pebble or R. L. G., was there a complete absence of sulphide, as in *three* instances, at the higher pressures, with F. G. powders. We feel bound again to lay stress upon the fact that there were no accidents of manipulation to account for these remarkable differences in residues furnished by powders of practically the same composition.

5. One or two other points of interest present themselves in connection with the potassium sulphate found in the residues from the three powders. Both in the pebble and F. G. residues, those obtained at the lowest and the highest densities differed very decidedly from the remainder in regard to the sulphate present, while the proportions in the residues obtained at the densities intermediate between those two extremes present comparatively slight differences in the case of both these powders. But the residues furnished by R. L. G. powder exhibit a very decided difference to the above; the proportions of sulphate in those produced at the four lowest pressures (up to a density of 40) are high, and very similar in amount to those found in the majority of the F. G. powder residues, while those in the residues produced at the six higher pressures are only from one-fourth to one-half in amount of the others, some being similar to, and others still lower than those formed in the pebble-powder residues. On comparing

the proportions of hyposulphite and sulphide in these R. L. G. residues with the sulphate, it will be seen that they vary as much among themselves in the residues where the proportion of sulphate is high as in those where it is small in amount. That the amount of sulphate produced by the explosion of this particular powder, even under the same conditions as regards pressure, was liable to considerable variation, is demonstrated by comparing the results of special examination of the residue obtained by its explosion in 40 per cent. space (as given in Table 3, page 245) with those in the general series (Tables 1 and 2) furnished by the same powder, fired in the same space. In the one instance 22·87 per cent. of sulphate were found, in the other it was barely half that amount. With such variations occurring in the proportion of *sulphate* formed under like conditions of explosions, it can hardly be matter for surprise that variations of the same kind should occur in the proportions of sulphide and hyposulphite. In fact, in the two parallel experiments now referred to, the amount of sulphide contained in the residue rich in sulphate was only about one-fifth that contained in the other residue, the proportion in this being higher than any in the three series of analyses. Be it observed, at the same time, that this high amount cannot be ascribed to the adoption of any special precautions to prevent accidental oxidation of the sulphide in the special experiment in which it was found, as there were several residues in the series furnished by *pebble*-powder (of the same composition as the R. L. G.) which contained proportions of sulphide not much lower than in this particular case.

Two other parallel experiments (39 and 96) with R. L. G. conducted in 60 per cent. space, exhibit, on the other hand, a remarkably close concordance in regard to the proportions of sulphate and hyposulphite (the numbers being almost identical), though there was a decidedly higher proportion of sulphide in the one than in the other, and a not unimportant difference in the proportions of the gaseous constituents.

With regard to the results of the special experiment with *pebble*-powder (p. 245) conducted in 40 per cent. space, and the parallel experiment in the series of pebble-powder results, it will be seen that the amounts of sulphate formed in the two experiments were closely similar. The proportions of sulphide and hyposulphite found in the residue of the special experiment correspond very well with the results obtained with this powder at the two lower and the next higher densities, which is not the case with the parallel experiment in the series (No. 12, 40 per cent.), and this may possibly indicate

that, in the latter, there may have been an exceptionally considerable conversion of sulphide into hyposulphite during the removal of the residue from the explosion-vessel, it being borne in mind that marked differences in the behaviour and appearance of the residues (even those resulting from the service-powder) were frequently noted at the time of collection.

Before leaving this part of our subject, we may remark that we have placed in the appendix to this memoir a statement, in which we have given for every analysis we have made, the results of the following rather laborious calculations, which have been made in the manner described in our first memoir:—*

(1) The amount of gaseous products calculated from the data furnished by the analysis of the solid products.

(2) The amount of solid products calculated from the data furnished by the analysis of the gaseous products.

(3) A comparison between the weights of the elementary substances found in the products of combustion and the weights of the same elements found in the powder prior to ignition.

(4) The weight of oxygen contained in the total quantity of hyposulphite found.

An examination of this statement will show how closely accordant the various analyses are as a whole; but in estimating the degree of accuracy attained, the following points must carefully be borne in mind.

1. That in the very large quantity of powder used, slight variations in its composition (as indeed have been found) were sure to exist.

2. That we have adopted as one of the data of our calculations the average quantity of gas found to be produced by the explosion. But, as we have elsewhere pointed out, our investigations seem to prove that exceedingly slight and inappreciable variations in the circumstances of explosion give rise to very notable changes in the products, and among others in the amount of gaseous products. Any change in this direction would of course affect the accordance of the analysis in which the abnormal decomposition occurred.

A review of the comparison between the weight of oxygen originally in the powder, and the weight found in the products of explosion, appears to show that there is in the former, on the average, a very appreciable excess of oxygen. Hence it may pretty fairly be concluded that a portion of the hyposulphite found is due to the oxidation of the monosulphide after removal from the explosion-vessel.

* *Phil. Trans.*, 1875, part i., p. 90.

On the other hand, a reference to those analyses in which hyposulphite exists in *large* proportion, shows that were we to assume the whole of the hyposulphite as formed after the removal of the products from the cylinders, there would exist a deficiency in oxygen much larger than the existing excess. Hence we may equally fairly, from this line of argument, conclude that it is impossible to attribute to accidental causes the formation of the whole of the hyposulphite, and that a considerable proportion of it *must* be looked on either as a primary or secondary product.

We now pass to the question of the amount of heat generated by the combustion of gunpowder, and in so doing we may remark that we were fully cognisant of the inconveniences inseparable from the form of apparatus used by us for this purpose and described in our first memoir.* In fact, the errors likely to arise from its use were very exactly pointed out by ourselves,† and we were quite aware of the great advantages in regard to saving of time and labour, and to accuracy, that would result from the use of apparatus similar to that which we shall presently describe.

But the apparatus, such as it was, was deliberately adopted, because at the time when these experiments were made we could not be sure that the decomposition experienced by gunpowder in its explosion, when fired in considerable quantities and under tensions similar to those existing in the bores of guns, was by any means the same as that occurring when it is fired in small quantities and under feeble tensions. In fact, one of the principal objects of our experiments was to determine the heat generated when gunpowder is fired in considerable quantities and under high tensions.

To do this, vessels of great strength, consequently of great weight, and therefore not well suited for calorimetric observations, were necessary.

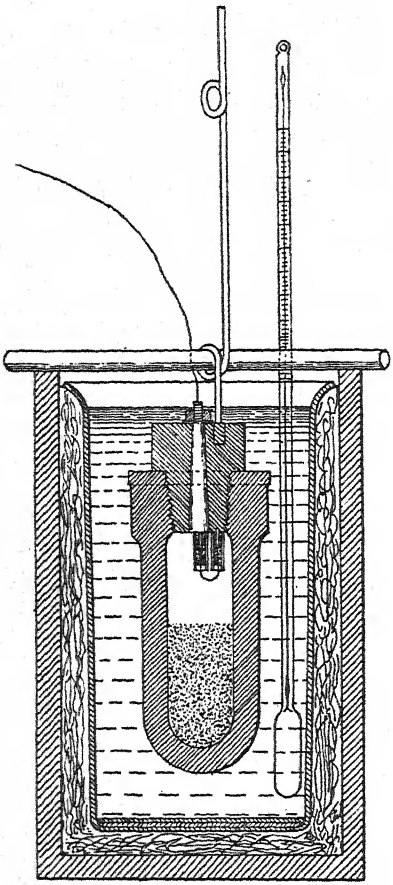
It will presently be seen, however, that the difference between the determinations made by us and those of the other experimenters alluded to by General Morin and M. Berthelot are due, not to error in our determinations, but to essential and striking differences in the decomposition of different descriptions of powder.

The conclusion of the whole of our analyses (of which a complete table is given at p. 236 of this memoir) has shown that, with certain slight exceptions, to which we have elsewhere adverted, the products of combustion are not seriously affected either by differences in the

* *Phil. Trans.*, 1875, part i., p. 63. † *Loc. cit.*, same page.

quantity or the gravimetric density of the charge exploded. It would appear indeed as if there were occasionally quite as great differences in the transformation which takes place between charges exploded as nearly as possible under the same circumstances and others exploded under widely different conditions.

We were therefore enabled in the experiments which we are about to describe, to make use of the following apparatus:—



Two explosion-vessels, both of the general form shown in the annexed figure, but weighing, one, 21,311·6 grs. (1381 grms.), with a capacity of 501·54 grs. (32·50 grms.), the other weighing 52,931·6 grs. (3430 grms.), with a capacity of 1833·75 grs. (118·83 grms.), were prepared. The specific heats of both these vessels were carefully determined, and the amount of heat absorbed by the calorimeter for various changes of temperature was also carefully determined, and corresponding tables for convenient use formed. Thermometers specially made for the purpose, and capable of being read to 0°·01 Fahr. (0°·0055 Cent.), were used in these experiments.

Full details of the determination of the specific heat of the vessels and of the absorption of the heat by the calorimeter are given in the appendix, pp. 297 to 300.

To determine the heat generated, a charge of from 150 to 200 grs. (9·72 to 12·96 grms.) in the smaller cylinder, of 400 grs. (25·92 grms.) in the larger cylinder, was carefully weighed and placed in the explosion-vessel. The explosion-vessel was then immersed in the water of the calorimeter and the charge fired in the usual way, the attached thermometer being read before the explosion, and afterwards

continuously until the maximum temperature (which was usually reached in about two minutes) was attained.*

In order to make our new calorimetric determinations as complete as possible, and with the view of exhibiting the differences in the heat evolved due to changes in the composition of the powder, we have not only found separately the heat given off by the three principal powders described in our first memoir, but have added to these three other powders differing widely in their composition, viz.: ordinary English mining, Curtis and Harvey's well-known powder No. 6, and Spanish spherical. The composition of all these powders has been already given either in the present or in our former memoir. But for our present purpose it is convenient to place in juxtaposition the composition of these six powders.

TABLE 4.—*Exhibiting the differences in the composition of the powders experimented with, which are described in this memoir.*

Nature of powder.	Saltpetre.	Sulphate.	Potassium chloride.	Sulphur.	Carbon.	Hydrogen.	Oxygen.	Ash.	Water.
Pebble-powder .	·7467	·0009	...	·1007	·1212	·0042	·0145	·0023	·0095
R. L. G., W. A.	·7443	·0013	...	·1009	·1240	·0040	·0127	·0022	·0106
F. G., W. A. .	·7355	·0036	...	·1002	·1136	·0049	·0257	·0017	·0148
Curtis and Harvey's No. 6 .	·7440	·0029	Trace	·1037	·1066	·0052	·0229	·0031	·0117
Mining powder .	·6166	·0012	·0014	·1506	·1793	·0066	·0223	·0059	·0161
Spanish spherical	·7530	·0027	·0002	·1242	·0865	·0038	·0168	·0063	·0065

The decomposition they experienced is exhibited in Tables 1 † and 2 of the present memoir.

With the small explosion-vessel the results obtained (Experiments 146 to 166, pp. 299, etc.) were as follows, the numbers given below indicating the grm.-units of heat evolved by the combustion of 1 gramme of each description of powder employed:—

Nature of powder.	Gramme-units of heat evolved.				
	I.	II.	III.	IV.	Means.
Pebble	711·9	734·1	694·4	710·0	712·6
R. L. G.	725·1	718·4	707·5	...	717·0
F. G.	706·5	738·9	731·7	...	725·7
Curtis and Harvey's No 6 .	784·0	755·7	744·9	732·9	754·3
Mining	512·7	505·5	507·9	...	508·7
Spanish	762·5	771·4	753·4	...	762·4

* It is scarcely necessary to state that the correction for the absorption of heat by the calorimeter and the effect of cooling was in all cases made.

† See also Tables 12 and 13 (pp. 310 and 312).

With the larger explosion-vessel the results of Experiments 171 to 179, and 181 to 192 (pp. 304, etc.), gave:—

Nature of powder.	Gramme-units of heat evolved.			
	I.	II.	III.	Means.
Pebble	728·5	714·7	703·4	715·5
R. L. G.	713·4	724·7	717·7	718·6
F. G.	731·1	722·1	730·7	728·0
Curtis and Harvey's No. 6 .	751·3	765·3	750·6	756·1
Mining	520·0	507·0	499·6	508·9
Spanish	771·3	761·8	754·0	762·3

From the whole of these experiments, and giving to the second series, as probably the more accurate, twice the weight of the first series, we arrive at the conclusion that the heat generated by the combustion of the powders *as actually used* is as follows:—

1	grm. of	pebble-powder	generates	714·5	grm.-units.
1	,,	R. L. G. ,,	,,	718·1	,,
1	,,	F. G. ,,	,,	727·2	,,
1	,,	C. and H. No. 6	,,	755·5	,,
1	,,	mining ,,	,,	508·8	,,
1	,,	Spanish ,,	,,	762·3	,,

From an examination of the whole of the above results it is obvious: Firstly, that the heat generated by the combustion of gunpowder is subject to very wide variations, dependent upon the particular nature * of the powder employed (the Spanish powder, for example, generates just 50 per cent. more heat than the mining powder); and, secondly, that the heat evolved by the same description of powder varies in different experiments to a greater extent than is to be accounted for by errors of observation. And this was, indeed, to be expected, since the very considerable variations in the products of combustion, under the same circumstances, as disclosed by our analyses, could hardly be supposed to exist without some corresponding variation in the heat evolved.

Our views on this head are confirmed by the calorimetric determinations we have made in our reseaches on gun-cotton. In these determinations, which have been carried on with precisely the same apparatus, we have found no appreciable difference in the heat evolved in the various experiments. The deduction is that the

* Both physical and chemical.

discrepancies between the several observations in the case of gunpowder are due to differences in the metamorphoses, not to defects in the observations.

The units of heat liberated given above are those furnished by the powders as actually used; but as these powders had different amounts of moisture in their composition, and as, in use, these amounts of moisture are found to vary considerably, giving rise, especially when the powders are used in guns, to very different pressures, and generating very different energies, we have considered it desirable to correct the above figures, and we place below those that would have had place had the powders, when fired, been perfectly free from moisture.

TABLE 5.—*Showing the heat, in gramme-units, generated by the combustion of* 1 *gramme of the undermentioned perfectly dry powders.*

1	grm.	pebble-powder	generates	721·4	grm.-units.
1	,,	W. A. R. L. G. powder	,,	725·7	,,
1	,,	W. A. F. G. powder	,,	738·3	,,
1	,,	C. and H. No. 6 powder	,,	764·4	,,
1	,,	mining powder	,,	516·8	,,
1	,,	Spanish pellet powder	,,	767·3	,,

The data for computing the mean specific heats of the products of explosion of the six powders, as well as the results of the necessary calculations, are given in the annexed Table, No. 6, p. 260.

We have pointed out in our first memoir our reasons for considering fallacious a temperature of explosion deduced (as has been done by some authors) by dividing the number of gramme-units of heat by the mean specific heat of the exploded powder at 0° Cent.; but for purposes of comparison, to exhibit the striking differences between the powders, as well as because we have not data at our disposal to enable us to deduce the actual temperature of explosion in the case of each of the six powders, we give below the temperature of each powder calculated upon the above hypothesis.

They are as follow:—

Temperature of explosion on above hypothesis of—

W. A.	pebble-powder	3899° Cent.
W. A. R. L. G.	,,	3880° ,,
W. A. F. G.	,,	3897° ,,
C. and H. No. 6	,,	4083° ,,
Mining	,,	2896° ,,
Spanish pellet	,,	4087° ,,

TABLE 6.—*Giving data and results of calculation of the mean specific heats (at natural temperatures) of the products of explosion of the six powders experimented with.*

Products of combustion.	A. Specific heat.	Pebble, W. A.		R. L. G., W. A.		F. G., W. A.		Curtis and Harvey's No. 6.		Mining.		Spanish spherical.	
		1. Weight in a grm.	Product of cols. A. and 1.	2. Weight in a grm.	Product of cols. A. and 2.	3. Weight in a grm.	Product of cols. A. and 3.	4. Weight in a grm.	Product of cols. A. and 4.	5. Weight in a grm.	Product of cols. A. and 5.	6. Weight in a grm.	Product of cols. A. and 6.
Carbonic anhydride	·172	·2651	·04560	·2608	·04486	·2634	·04530	·2606	·04482	·2290	·03939	·2438	·04193
Carbonic oxide	·174	·0473	·00823	·0418	·00727	·0348	·00605	·0248	·00431	·1531	·02664	·0140	·00244
Nitrogen	·173	·1110	·01920	·1106	·01913	·1100	·01903	·1137	·01977	·0861	·01489	·1097	·01898
Sulphydric acid	·184	·0110	·00202	·0107	·00197	·0100	·00184	·0083	·00153	·0391	·00719	·0097	·00178
Marsh-gas	·468	·0006	·00028	·0008	·00037	·0003	·00014	·0046	·00215	·0071	·00332	...	...
Hydrogen	2·411	·0006	·00145	·0005	·00121	·0007	·00169	·0008	·00193	·0017	·00410	·0003	·00072
Oxygen	·155	...	...	·0002	·00003	·0003	·00005	...	...	...	...	·0007	·00011
Potassium carbonate	·206	·3226	·06646	·3392	·06987	·2804	·05776	·3436	·07078	·1970	·04058	·2173	·04476
,, sulphate	·196	·0703	·01378	·0838	·01642	·1225	·02401	·1258	·02466	·0028	·00055	·2962	·05805
,, hyposulphite	·197	·0789	·01554	·0760	·01497	·1440	·02837	·0231	·00455	·0281	·00554	·0473	·00932
,, monosulphide	·108	·0574	·00620	·0360	·00387	·0140	·00151	·0589	·00636	·1612	·01741	·0197	·00213
,, sulphocyanate	·200	·0016	·00032	·0013	·00026	·0007	·00014	...	...	·0140	·00280	·0003	·00006
,, nitrate	·239	·0013	·00031	·0015	·00036	·0009	·00021	·0017	·00041	·0004	·00010	·0058	·00139
,, oxide	·200	·0009	·00018	...	...	·0075	·00150	...	...	...	...	...	...
,, sesquicarbonate	·350	·0005	·00017	·0004	·00014	·0003	·00010	·0005	·00018	·0085	·00298	·0002	·00007
Sulphur	·171	·0309	·00528	·0357	·00610	·0102	·00174	·0336	·00575	·0623	·01065	·0350	·00598
Charcoal	·242	...	...	·0007	·00017	...	...	...	...	·0096	·00232	...	...
Mean specific heats	...	...	·18503	...	·18704	...	·18946	...	·18720	...	·17846	...	·18773

There is no material difference in the specific heats if the hyposulphite be supposed to be an accidental product formed by the oxidation of the sulphide.

The volumes of the permanent gases generated by the explosion of each of the six powders are as follow:—

1 grm. of	W. A.	pebble-powder	generated	275·7	c.c.
1 ,,	W. A. R. L. G.	,,	,,	271·3	,,
1 ,,	W. A. F. G.	,,	,,	259·2	,,
1 ,,	C. and H. No. 6	,,	,,	238·2	,,
1 ,,	mining	,,	,,	354·6	,,
1 ,,	Spanish pellet	,,	,,	232·7	,,

The above volumes are all calculated for a temperature of 0° Cent. and a barometric pressure of 760 mm. of mercury.

If we correct, as before, the quantities of permanent gases formed for the amounts of moisture contained in the powders when experimented with, we shall have the values given in Table 7.

TABLE 7.—*Giving the volumes of permanent gases generated by the explosion of 1 gramme of the undermentioned perfectly dry powders.*

1 grm.	W. A.	pebble-powder	generates	278·3	c.c.*
1 ,,	W. A. R. L. G.	,,	,,	274·2	,,
1 ,,	W. A. F. G.	,,	,,	263·1	,,
1 ,,	C. and H. No. 6	,,	,,	241·0	,,
1 ,,	mining	,,	,,	360·3	,,
1 ,,	Spanish pellet	,,	,,	234·2	,,

It is of high importance to observe that the volume of the permanent gases generated is, in every case, in inverse ratio to the units of heat evolved. Thus, if Tables 5 and 7 be compared, and if from Table 5 we arrange the powders in descending order of units of heat, we have the order exhibited in Table 8; and if from Table 7 we place the powders in ascending order of volumes of gas produced, we find that we have precisely the same arrangement.

TABLE 8.—*Showing the arrangement of the six powders when placed either according to the amount of heat generated in a descending, or according to the quantity of gas evolved in an ascending, scale.*

Nature of powder.	Units of heat per gramme exploded.	Cubic centimetres of gas per gramme exploded.
Spanish pellet powder	767·3	234·2
Curtis and Harvey's No 6	764·4	241·0
W. A. F. G. powder	738·3	263·1
W. A. R. L. G. powder	725·7	274·2
W. A. pebble-powder	721·4	278·3
Mining powder	516·8	360·3

* It is perhaps necessary to remind readers not familiar with the French metrical system that the assertion that a grm. of powder generates 278·3 c.c. of

The results given in this table are very striking. If we take the two natures which commence and close the list, it will be observed that on the one hand the heat generated by the Spanish powder is about 50 per cent. higher than that generated by the mining powder, and that on the other hand the quantity of permanent gases evolved by the mining powder is about 50 per cent. greater than that given off by the Spanish.

Thus it appears that the great inferiority of heat developed by the mining as compared with the Spanish powder is compensated, or at least approximately so, by the great superiority in volume of permanent gases produced. A similar relation is observed in respect to the other powders, and it may indeed be noted that the products of the figures given in columns 2 and 3 in Table 8 do not differ greatly from a constant value; thus pointing towards the conclusion that the pressures at any given density and the capacity for performing work of the various powders are not very materially different.

This fact has been entirely verified for the whole of the Waltham-Abbey powders, and in a less degree for the three other powders also.

Thus at the points where the Spanish, mining, and Curtis and Harvey's No. 6 powders have been compared with the standard pressure curves determined from Waltham-Abbey powder, the agreement is very close; the departure from the normal curve not in any case exceeding that obtained in particular experiments with the Waltham-Abbey powders themselves.

With respect to the pressure given by mining powder, the peculiarities shown by this powder were so interesting that it appeared to us important to determine its tension when fired under a high gravimetric density. We accordingly fired (Experiment 230) 11,560 grs. (749 grms.) of this powder under a gravimetric density of unity.

The pressures developed by two very accordant observations was, when corrected, 44 tons on the square inch (6706 atmospheres). The pressure obtained under similar circumstances from Waltham-Abbey powder was 43 tons on the square inch (6554 atmospheres).

It will afterwards be seen that the capacity for performing work of the various descriptions of powder is also not very different, and this similarity of result is the more remarkable when it is remembered that with, at all events, three of the powders, there

permanent gases at temperature and pressure specified, is equivalent to the assertion that the permanent gases occupy 278·3 times the space which the powder occupied in its unexploded state, the gravimetric density of the powder being assumed to be unity.

were striking differences both in their composition and in the decomposition that they experienced, and when, in consequence, material variations both in pressures at different densities and in potential energy might have been expected.

But returning to the great difference in heat evolved, for example, by the Spanish and mining powders, we think it is difficult to resist the conclusion that the small number of units of heat evolved by the latter is in great measure due to the quantity of heat that has been absorbed in placing the very much larger proportion of the products of combustion in the form of permanent gases. This suggestion would, we think, also fully explain the fact alluded to in our first memoir,* and to which we had been led purely by experiment, namely, "that the variations observed by us in the decomposition of gunpowder do not, even when very considerable, materially affect either its tension or capacity for performing work."

The above facts and remarks would also show that a comparison between different gunpowders, or a comparison between gunpowder and other explosive agents cannot, as has been proposed,† be determined by a simple measurement of the corresponding units of heat they evolve.

Did such a law hold, the Spanish powder should have more than 50 per cent. advantage over the mining powder, but as a matter of fact, although not very widely different, the mining powder had the advantage, both in respect to the tension observed in a close vessel and to the energy developed in the bore of a gun.

As regards the *actual* temperature of explosion, we have little doubt, from the results of the further experiments detailed in this paper, that the temperature named in our first memoir, viz., 2200° Cent., is not far removed from the truth for the principal powders with which we were then experimenting.

That temperature may not improbably be taken at the high limit of the temperature of explosion for the Spanish pellet, which, as conjectured by us, has been proved to have developed a higher temperature than any other powder with which we have experimented.

The complete fusion of the platinum with this powder, and with this alone, is thus shown not to be an isolated or accidental occurrence, but to depend on a real difference of temperature, and we are thus by two converging lines of reasoning brought to the conclusion that for pebble or R. L. G. powder the temperature of explosion may be taken as a little above the melting-point of platinum, say about

* P. 150, *ante*.

† De Tromenec, *Comptes Rendus*, tom. lxxvii., p. 128.

2100° Cent., while the temperature of explosion of a powder like the Spanish pellet may be taken as occasionally ranging up to 2200° Cent.

The data at our disposal are not sufficient to enable us to determine the temperature of explosion of the English mining powder with the same accuracy, but it is probable that 2000° Cent. and 1800° Cent. may be assigned as the limits between which the true temperature may be placed.

After our remarks on the slight differences or accidents which appear to give rise to not inconsiderable variations in the products of decomposition of gunpowder, it is hardly necessary to point out that such differences in decomposition are nearly sure to give rise to corresponding variations in the temperature of explosion, and that therefore this temperature, even in one and the same powder, cannot be supposed to be always identical.*

The relation between the tension of the gases developed by the explosion of gunpowder (when it is expanded in the bore of a gun with production of work) and the volume which these gases occupy, is in our first memoir † expressed by the relation

$$\frac{p}{p_0} = \left\{\frac{v_0(1-\alpha)}{v-\alpha v_0}\right\}^{\frac{C_p+\beta\lambda}{C_v+\beta\lambda}} \quad . \quad . \quad . \quad (30)$$

where p is the tension of the permanent gases corresponding to volume v, C_p the specific heat of the permanent gases at constant pressure, C_v the specific heat at constant volume, α the ratio which the volume of the non-gaseous products of explosion bears to the volume of the unexploded powder, β the ratio between the weights of the non-gaseous and gaseous portions of the products of explosion, λ the specific heat of the non-gaseous products; but in that memoir the values of the constants C_p, C_v, and β were calculated from a few of the analyses that were first made. The completion of the whole of our analyses has enabled us to recalculate these three constants, and their values, together with those of the other constants used in Equation (30), are given in Table 9, p. 266.

With regard to the value of λ it is necessary to say a few words. If the tensions given in Table 18,‡ of our first memoir, calculated from (30), be compared with the tensions actually observed in the bores of guns given in the same table, or if a comparison be made between curves B and C in Plate XX. (p. 230) of the same memoir, it will

* It is by no means improbable that owing to the larger proportion of carbon which assumes the higher state of oxidation as the pressure under which the explosion takes place is increased, the temperatures at high tensions may be somewhat greater than those which occur when the powder is fired under low tensions.

† *Phil. Trans.*, 1875, part i., p. 129. ‡ P. 200, *ante*.

be observed that for densities of the products of combustion of ·4 and below, or, in other words, for $2\frac{1}{2}$ expansions and higher, the tensions actually observed with R. L. G. powder are in all cases higher than those calculated from Equation (30). This, of course, should not be, as those last tensions should in actual practice only be reached if there were no loss from windage, vent, or other causes, if there were perfect combustion of the charge, and if the charge were expanded in a gun perfectly impervious to heat.

We surmised * as one of the causes of this difference that in our calculations we had taken λ at its mean value, whereas we pointed out that as the specific heat of the non-gaseous products must, according to our hypothesis, increase rapidly with the temperature, λ should for our purposes be taken at a considerably higher value.

As however the agreement between the observed and calculated tensions was exceedingly close, as when the calculations were applied to guns, the "factor of effect" alone would practically be altered, and as, finally, we had not sufficient data to enable us to correct this constant with any certainty, we did not feel justified in attempting hypothetical corrections.

But since the date of the submission of our first memoir to the Royal Society, our knowledge of the action of large charges in the bores of guns has been greatly increased; not only have charges seven or eight times as great † as the largest of those then discussed been fired, but we have submitted to careful calculation, with a full knowledge of all the necessary data, the results of a very large number of rounds fired from guns of all sizes, from the 100-ton gun down to the smallest gun in H.B.M.'s service. In some of these guns also the charges were so arranged as to suffer a high degree of expansion, and we have thus accumulated data which have enabled us to deduce a corrected value of λ, and which gives pressures and energies more closely in accordance with the whole of the experiments we have discussed.

The value of p_0, that is, the pressure corresponding to a gravimetric density of unity, is taken at 6554 atmospheres = 43 tons per

* *Phil. Trans.*, loc. cit., p. 131.

† The highest charge fired by the distinguished Italian artillerists who conducted the recent experiments with the 100-ton guns reached the great weight of 260 kilos. (573 lbs.) of Fossano powder—a powder singularly well adapted for use in large guns. The velocity given to a projectile of 908 kilos. (2001·5 lbs.) was (525·9 metres) 1725·3 feet per second, and the energy of the shot at the muzzle reached the enormous amount of (12,800 metre tonnes) 41,333 foot-tons. The highest charge fired from the 80-ton gun has been (208·7 kilos.) 460 lbs. prismatic powder. This charge gave to a projectile of 1705 lbs. a muzzle velocity of (495·6 metres) 1626 feet per second and an energy of (9680 metre tonnes) 31,257 foot-tons.

square inch, this value being the result of our further experiments corrected for perfectly dry powder.

TABLE 9.—*Showing the value of the constants in Equation* (30).

$$
\begin{aligned}
p_0 &= 43 \text{ tons per square inch} = 6554 \text{ atmospheres.} \\
a &= \cdot 57 \\
\beta &= 1\cdot 2957 \\
C_p &= \cdot 2324 \\
C_v &= \cdot 1762 \\
\lambda &= \cdot 45.
\end{aligned}
$$

From Equation (30), with the values of the constants given in Table 9, we have calculated the tensions for various gravimetric densities ranging from 1 to ·05, and have expressed these tensions in kilogrammes per square centimetre, in tons per square inch, and in atmospheres.

We have placed in the same table, for purposes of comparison, the pressures which would rule were the gases permitted to expand without production of work in a vessel impervious to heat, or, what amounts to the same thing, the pressures that would have place where the charges exploded in a perfectly closed cylinder, with the corresponding gravimetric densities.

We have shown* that the theoretic work which a charge of gunpowder is capable of effecting in expanding to any volume (v) is expressed by the equation

$$
W = \frac{p_0 v_0 (1-a)(C_v + \beta\lambda)}{C_p - C_v}\left\{1 - \left(\frac{v_0(1-a)}{v - av_0}\right)^{\frac{C_p - C_v}{C_v + \beta\lambda}}\right\} \quad . \quad (34)
$$

And on account of its very great utility, we give in Table 11, pp. 268-271, the results of the calculations of W for various values of v up to and inclusive of $v = 50$, the powder used being supposed to be of the normal type and free from moisture, and the constants having the values given in Table 9.

The work is expressed in the table both in metre tonnes per kilogramme and foot-tons per pound of powder burned, and, by use of a proper factor of effect, is applicable also to powders differing very materially from those of Waltham-Abbey manufacture—for example, to mining or the Spanish powders.

But before entering upon these special cases we shall, as the principles embodied in this table have led to the greatly increased charges of recent guns, and the consequent high velocities attained, give one or two illustrations of its application.

* *Phil. Trans.*, 1875, part i., p. 132.

TABLE 10.—*Giving in terms of the density the tensions existing in the bores of guns, calculated from Equation* (30); *giving also the tensions if the gases are suffered to expand without production of work. In both cases the powder is supposed to be perfectly dry.*

Mean density of products of combustion.	Corresponding expansions.	Tensions calculated from Equation (30).						Tensions in close cylinders, or where gases expand without cooling or production of work.					
		Kilos. per square cm.	Differences.	Tons per square inch.	Differences.	Atmospheres.*	Differences.	Kilos. per square cm.	Differences.	Tons per square inch.	Differences.	Atmospheres.	Differences.
1·00	1·000	6772·2	789·0	43·00	5·01	6554·0	763·6	6772·2	738·6	43·00	4·69	6554·0	715·9
·95	1·053	5983·2	693·0	37·99	4·40	5790·4	670·7	6033·6	652·1	38·31	4·14	5839·1	631·0
·90	1·111	5290·2	609·5	33·59	3·88	5119·7	589·8	5381·5	579·5	34·17	3·68	5208·1	560·9
·85	1·176	4680·7	541·8	29·72	3·44	4529·9	524·4	4802·0	519·8	30·49	3·30	4647·2	503·0
·80	1·250	4138·9	481·9	26·28	3·07	4005·5	466·4	4282·2	467·7	27·19	2·97	4144·2	452·6
·75	1·333	3657·0	434·7	23·22	2·76	3539·1	420·6	3814·5	422·1	24·22	2·68	3691·6	408·5
·70	1·429	3222·3	390·6	20·46	2·48	3118·5	378·0	3392·4	385·9	21·54	2·45	3283·1	373·4
·65	1·539	2831·7	354·3	17·98	2·25	2740·5	343·0	3006·5	351·2	19·09	2·23	2909·7	339·9
·60	1·667	2477·4	321·3	15·73	2·04	2397·5	310·9	2655·3	322·8	16·86	2·05	2569·8	312·5
·55	1·818	2156·1	292·9	13·69	1·86	2086·6	283·5	2332·5	296·1	14·81	1·88	2257·3	286·5
·50	2·000	1863·2	267·8	11·83	1·70	1803·1	259·1	2036·4	274·1	12·93	1·74	1970·8	265·2
·45	2·222	1595·4	245·7	10·13	1·56	1544·0	237·8	1762·3	253·5	11·19	1·61	1705·6	245·4
·40	2·500	1349·7	225·2	8·57	1·43	1306·2	217·9	1508·8	236·3	9·58	1·50	1460·2	228·7
·35	2·857	1124·5	206·3	7·14	1·31	1088·3	199·7	1272·5	218·9	8·08	1·39	1231·5	211·8
·30	3·333	918·2	190·6	5·83	1·21	888·6	184·4	1053·6	204·7	6·69	1·30	1019·7	198·2
·25	4·000	727·6	174·8	4·62	1·11	704·2	169·2	848·9	192·2	5·39	1·22	821·5	185·9
·20	5·000	552·8	160·6	3·51	1·02	535·0	155·5	656·7	179·5	4·17	1·14	635·6	173·8
·15	6·667	392·2	146·5	2·49	·93	379·5	141·7	477·2	168·5	3·03	1·07	461·8	163·1
·10	10·000	245·7	132·3	1·56	·84	237·8	128·1	308·7	159·1	1·96	1·01	298·7	153·9
·05	20·000	113·4		·72		109·7		149·6		·95		144·8	

* We are indebted to Colonel Aloncle and the Commandant Hedon, of the Marine Artillery of France, translators of our memoir, for pointing out that although we have adopted as our standard atmosphere that used in France, viz., a barometric pressure of 760 mm. mercury and a temperature of 0° Cent., the coefficient we have used in converting tons per square inch into atmospheres is not exactly in accordance with our supposition. In the present memoir this discrepancy is corrected.

TABLE 11.—*Giving for value of* v *up to* v=50, *the total work that dry gunpowder of the Waltham-Abbey standard is capable of performing in the bore of a gun in metre tonnes per kilogramme, and foot-tons per lb. of powder burned.*

Number of volumes of expansion.	Corresponding density of products of combustion.	Total work that gunpowder is capable of performing.			
		Per kilog. burned in metre tonnes.	Difference.	Per lb. burned in foot-tons.	Difference.
1·00	1·000	...	...	...	...
1·01	·990	0·669	·669	·980	·980
1·02	·980	1·322	·653	1·936	·956
1·03	·971	1·960	·638	2·870	·934
1·04	·962	2·583	·623	3·782	·912
1·05	·952	3·192	·609	4·674	·892
1·06	·943	3·788	·596	5·547	·873
1·07	·935	4·370	·582	6·399	·852
1·08	·926	4·940	·570	7·234	·835
1·09	·917	5·498	·558	8·051	·817
1·10	·909	6·045	·547	8·852	·810
1·11	·901	6·581	·536	9·637	·785
1·12	·893	7·106	·525	10·406	·769
1·13	·885	7·621	·515	11·160	·754
1·14	·877	8·126	·505	11·899	·739
1·15	·870	8·622	·496	12·625	·726
1·16	·862	9·109	·487	13·338	·713
1·17	·855	9·587	·478	14·038	·700
1·18	·847	10·056	·469	14·725	·687
1·19	·840	10·517	·461	15·400	·675
1·20	·833	10·970	·453	16·063	·663
1·21	·826	11·416	·446	16·716	·653
1·22	·820	11·855	·439	17·359	·643
1·23	·813	12·287	·432	17·992	·633
1·24	·806	12·712	·425	18·614	·622
1·25	·800	13·130	·418	19·226	·612
1·26	·794	13·541	·411	19·828	·602
1·27	·787	13·945	·404	20·420	·592
1·28	·781	14·342	·397	21·001	·581
1·29	·775	14·732	·390	21·572	·571
1·30	·769	15·115	·383	22·133	·561
1·32	·758	15·875	·760	23·246	1·113
1·34	·746	16·611	·736	24·324	1·078
1·36	·735	17·326	·715	25·371	1·047
1·38	·725	18·021	·695	26·389	1·018
1·40	·714	18·698	·677	27·380	·991
1·42	·704	19·358	·660	28·348	·968
1·44	·694	20·002	·644	29·291	·943
1·46	·685	20·630	·628	30·211	·920
1·48	·676	21·243	·613	31·109	·898
1·50	·667	21·842	·599	31·986	·877
1·52	·658	22·427	·585	32·843	·857
1·54	·649	22·999	·572	33·681	·838
1·56	·641	23·558	·559	34·500	·819
1·58	·633	24·105	·547	35·301	·801
1·60	·625	24·641	·536	36·086	·785
1·62	·617	25·166	·525	36·855	·769
1·64	·610	25·680	·514	37·608	·753
1·66	·602	26·184	·504	38·346	·738
1·68	·595	26·678	·494	39·069	·723
1·70	·588	27·162	·484	39·778	·709
1·72	·581	27·637	·475	40·474	·696

TABLE 11—*continued.*

Number of volumes of expansion.	Corresponding density of products of combustion.	Total work that gunpowder is capable of performing.			
		Per kilog. burned in metre tonnes.	Difference.	Per lb. burned in foot-tons.	Difference.
1·74	·575	28·103	·466	41·156	·682
1·76	·568	28·561	·458	41·827	·671
1·78	·562	29·011	·450	42·486	·659
1·80	·555	29·453	·442	43·133	·647
1·82	·549	29·887	·434	43·769	·636
1·84	·543	30·314	·427	44·394	·625
1·86	·537	30·734	·420	45·009	·615
1·88	·532	31·147	·413	45·614	·605
1·90	·526	31·553	·406	46·209	·595
1·92	·521	31·953	·400	46·795	·586
1·94	·515	32·347	·394	47·372	·577
1·96	·510	32·735	·388	47·940	·568
1·98	·505	33·117	·382	48·499	·559
2·00	·500	33·493	·376	49·050	·551
2·05	·488	34·403	·910	50·383	1·333
2·10	·476	35·284	·881	51·673	1·290
2·15	·465	36·137	·853	52·922	1·249
2·20	·454	36·963	·826	54·132	1·210
2·25	·444	37·763	·800	55·304	1·172
2·30	·435	38·538	·775	56·439	1·135
2·35	·425	39·289	·751	57·539	1·100
2·40	·417	40·017	·728	58·605	1·066
2·45	·408	40·723	·706	59·639	1·034
2·50	·400	41·408	·685	60·642	1·003
2·55	·392	42·073	·665	61·616	·974
2·60	·384	42·720	·647	62·563	·947
2·65	·377	43·350	·630	63·486	·923
2·70	·370	43·964	·614	64·385	·899
2·75	·363	44·563	·599	65·262	·877
2·80	·357	45·148	·585	66·119	·857
2·85	·351	45·719	·571	66·955	·836
2·90	·345	46·276	·557	67·771	·816
2·95	·339	46·820	·544	68·568	·797
3·00	·333	47·352	·532	69·347	·779
3·05	·328	47·872	·520	70·109	·762
3·10	·322	48·381	·509	70·854	·745
3·15	·317	48·880	·499	71·585	·731
3·20	·312	49·369	·489	72·301	·716
3·25	·308	49·848	·479	73·002	·701
3·30	·303	50·318	·470	73·690	·688
3·35	·298	50·779	·461	74·365	·675
3·40	·294	51·231	·452	75·027	·662
3·45	·290	51·675	·444	75·677	·650
3·50	·286	52·111	·436	76·315	·638
3·55	·282	52·539	·428	76·940	·625
3·60	·278	52·959	·420	77·553	·613
3·65	·274	53·371	·412	78·156	·603
3·70	·270	53·776	·405	78·749	·593
3·75	·266	54·174	·398	79·332	·583
3·80	·263	54·565	·391	79·905	·573
3·85	·260	54·950	·385	80·469	·564
3·90	·256	55·329	·379	81·024	·555
3·95	·253	55·702	·373	81·570	·546
4·00	·250	56·069	·367	82·107	·537
4·10	·244	56·786	·717	83·157	1·050

TABLE 11—*continued.*

Number of volumes of expansion.	Corresponding density of products of combustion.	Total work that gunpowder is capable of performing. Per kilog. burned in metre tonnes.	Difference.	Per lb. burned in foot-tons.	Difference.
4·20	·238	57·482	·696	84·176	1·019
4·30	·232	58·158	·676	85·166	·990
4·40	·227	58·815	·657	86·128	·962
4·50	·222	59·454	·639	87·064	·936
4·60	·217	60·076	·622	87·975	·911
4·70	·213	60·671	·605	88·861	·886
4·80	·208	61·260	·589	89·724	·863
4·90	·204	61·834	·574	90·565	·841
5·00	·200	62·394	·560	91·385	·820
5·10	·196	62·941	·547	92·186	·801
5·20	·192	63·475	·534	92·968	·782
5·30	·188	63·997	·522	93·732	·764
5·40	·185	64·507	·510	94·479	·747
5·50	·182	65·006	·499	95·210	·731
5·60	·178	65·494	·488	95·925	·715
5·70	·175	65·972	·478	96·625	·700
5·80	·172	66·440	·468	97·310	·685
5·90	·169	66·898	·458	97·981	·671
6·00	·166	67·347	·449	98·638	·657
6·10	·164	67·787	·440	99·282	·644
6·20	·161	68·219	·432	99·915	·633
6·30	·159	68·643	·424	100·536	·621
6·40	·156	69·059	·416	101·145	·609
6·50	·154	69·468	·409	101·744	·599
6·60	·151	69·870	·402	102·333	·589
6·70	·149	70·265	·395	102·912	·579
6·80	·147	70·653	·388	103·480	·568
6·90	·145	71·034	·381	104·038	·558
7·00	·143	71·411	·374	104·586	·548
7·10	·141	71·779	·368	105·125	·539
7·20	·139	72·141	·362	105·655	·530
7·30	·137	72·497	·356	106·176	·521
7·40	·135	72·847	·350	106·688	·512
7·50	·133	73·191	·344	107·192	·504
7·60	·131	73·530	·339	107·688	·496
7·70	·130	73·864	·334	108·177	·489
7·80	·128	74·193	·329	108·659	·482
7·90	·126	74·517	·324	109·133	·474
8·00	·125	74·836	·319	109·600	·467
8·10	·123	75·150	·314	110·060	·460
8·20	·122	75·460	·310	110·514	·454
8·30	·120	75·766	·306	110·962	·448
8·40	·119	76·068	·302	111·404	·442
8·50	·117	76·366	·298	111·840	·436
8·60	·116	76·660	·294	112·270	·430
8·70	·115	76·950	·290	112·695	·425
8·80	·114	77·236	·286	113·114	·419
8·90	·112	77·519	·283	113·528	·414
9·00	·111	77·798	·279	113·937	·409
9·10	·110	78·074	·276	114·341	·404
9·20	·109	78·346	·272	114·739	·398
9·30	·108	78·615	·269	115·133	·394
9·40	·106	78·880	·265	115·521	·388
9·50	·105	79·142	·262	115·905	·384
9·60	·104	79·401	·259	116·284	·379

TABLE 11—*concluded.*

Number of volumes of expansion.	Corresponding density of products of combustion.	Total work that gunpowder is capable of performing.			
		Per kilog. burned in metre tonnes.	Difference.	Per lb. burned in foot-tons.	Difference.
9·70	·103	79·657	·256	116·659	·375
9·80	·102	79·910	·253	117·029	·370
9·90	·101	80·160	·250	117·395	·366
10	·100	80·407	·247	117·757	·362
11	·091	82·734	2·327	121·165	3·408
12	·083	84·833	2·099	124·239	3·074
13	·077	86·743	1·910	127·036	2·797
14	·071	88·945	1·752	129·602	2·566
15	·066	90·112	1·617	131·970	2·368
16	·062	91·613	1·501	134·168	2·198
17	·059	93·013	1·400	136·218	2·050
18	·055	94·324	1·311	138·138	1·920
19	·052	95·557	1·233	139·944	1·806
20	·050	96·720	1·163	141·647	1·703
21	·047	97·820	1·100	143·258	1·611
22	·045	98·865	1·045	144·788	1·530
23	·043	99·858	·993	146·242	1·454
24	·042	100·805	·947	147·629	1·387
25	·040	101·709	·904	148·953	1·324
30	·033	105·701	3·992	154·800	5·847
35	·028	109·024	3·323	159·667	4·867
40	·025	111·865	2·841	163·828	4·161
45	·022	114·342	2·477	167·456	3·628
50	·020	116·537	2·195	170·671	3·215

Thus if we wish to know the maximum work of a given charge fired in a gun with such capacity of bore that the charge suffered five expansions during the motion of the projectile in the gun, the gravimetric density of the charge being unity, the table shows us that for every pound or kilogramme in the charge, an energy of 91·4 foot-tons or 62,394 kilogrammetres will as a maximum be generated.

If the factor of effect for the powder be known, the above values multiplied by that factor will give the energy per pound or kilogramme that may be expected to be raised in the projectile.

But it rarely happens, especially with the very large charges used in the most recent guns, that gravimetric densities so high as unity are employed, and in such cases, from the total realisable energy must be deducted the energy which the powder would have generated had it expanded from a density of unity to that actually occupied by the charge.

Thus, in the instance above given, if we suppose the charge instead of a gravimetric density of unity to have a gravimetric density of ·8, which corresponds to a volume of expansion of 1·25, we

see from Table 11 that from the 91·4 foot-tons or 62,394 kilogrammetres above given there must be subtracted* 19·23 foot-tons or 13,127·3 kilogrammetres, leaving 72·17 foot-tons or 49,272·8 kilogrammetres as the maximum energy realisable under the given conditions per pound or per kilogramme of the charge.

As before, these values must be multiplied by the factor of effect to obtain the energy realisable in the projectile.

But, to apply these principles to an actual case. The factor of effect of a certain brand of pebble-powder having been found in a powder-proof gun to be with that gun between ·82 and ·84, let us examine what are the energies likely to be realised with charges of 70, 90, and 100 lbs. in an 8-inch gun, of 130 and 140 lbs. in a 10-inch gun, and of 235 lbs. in an 11-inch gun.

We have selected these instances both because the same powder was used in the experiments, and because they offer considerable variety with respect to the number of expansions and the gravimetric densities of the charges.

Taking first the 8-inch gun. The number of expansions that the charges experienced in the bore of the gun and the original gravimetric densities of the charges, were as follow:—

For a charge of	70 lbs.,	number of expansions	6·12,	gravimetric density	·605
„ „	90	„ „	4·76,	„	·780
„ „	100	„ „	4·29,	„	·865

Hence, from Table 11, the maximum energy realisable is—

				Foot-tons per lb.
For the 70 lbs. charge,	99·4 foot-tons	– 37·60 foot-tons	=	61·80
„ 90 „	89·3 „	– 20·86 „	=	68·44
„ 100 „	84·9 „	– 13·66 „	=	71·24

Multiplying these energies by the factors of effect obtained from the proof of the powder and by the number of pounds in the charge, we should expect the energy realised from the

70 lbs. charge to lie between	3547·3	and	3633·8	foot-tons.
90 „ „	5050·9	„	5174·0	„
100 „ „	5841·7	„	5984·2	„

Compare now these results with the actual experiments. On firing the above charges, it was found that the 70 lbs. charge gave to a 180 lbs. shot a velocity of 1694 feet per second, corresponding to a

* This correction, as has been elsewhere pointed out by one of us, is only approximate.

total energy of 3637 foot-tons, the 90 lbs. charge a velocity of 2027 feet per second, or a total energy of 5133 foot-tons, and the 100 lbs. charge a velocity of 2182 feet per second, or an energy of 5940 foot-tons.

In the 10-inch gun the number of expansions and the gravimetric densities were—

For the charge of 130 lbs., number of expansions 4·294, $\left\{\begin{matrix}\text{gravimetric}\\ \text{density}\end{matrix}\right\}$ 0·792
„ „ 140 „ „ 4·050, „ 0·840

Hence, as before, the maximum energies realisable are found to be—

For the 130 lbs., 65·14 foot-tons per lb. (84·94 – 19·80)
„ 140 „ 66·84 „ „ (82·50 – 15·66)

and multiplying by the same factors of effect, the total energy realised would lie between 6943·9 and 7113·3 foot-tons for the former, and between 7673·2 and 7860·4 foot-tons for the latter charge.

The actual results obtained with the 10-inch gun were, for the 130 lbs. charge, a velocity of 1605 feet per second and an energy of 7158 foot-tons; for the 140 lbs. charge, a velocity of 1706 feet per second and an energy of 8092 foot-tons. With the 235 lbs. charge fired from the 11-inch gun the number of expansions was 4·214, the gravimetric density of the charge ·770, while the energy realised was found to be 13,066 foot-tons, or 55·6 foot-tons per pound of powder used.

It will be noted that with the 8-inch gun (it happens that this calibre is the same as that of the gun used for powder-proof, although the charges employed with this last are from one-half to one-third of those we are now discussing) the results realised are in each case very close to those predicted; ·84 as a factor of effect gives calculated results all but coincident with the high limit above given, but it must not be expected that results so closely accordant can always be obtained. Even when the same charges of the same powder and under precisely the same conditions are fired, considerable variations in energy sometimes have place. In the 10-inch gun, and with the larger charges of 130 and 140 lbs., it will be observed that the realised energies are in both instances higher than the highest expected energy above given. In other words, for this gun and these charges a factor of from ·85 to ·86 should be used instead of the factor ·84. Again, with the 11-inch gun, when the still larger charge

of 235 lbs. was employed, it will be found from the figures above given that the factor of effect for this gun, powder, and charge is about ·89.

Hence the factor of effect with the same powder has gradually increased from about ·83 in the powder-proof gun, to ·84 in the 8-inch gun, to ·86 in the 10-inch, and to ·89 in the 11-inch gun. And, generally, we must point out that not only may the factors of effect differ very much with the powders employed, being in this respect dependent upon circumstances, such as the density of the powder, its size of grain, amount of moisture, chemical composition, nature of charcoal used, etc., but they may also vary considerably even with the same powder if the charges be not fired under precisely the same circumstances. For example, especially with slow-burning powders, the weight of the shot fired exerts a very material influence upon the factor of effect, and the reason is obvious: the slower the shot moves at first, the earlier in its passage up the bore is the charge entirely consumed and the higher is the energy realised. The same effect, unless modified by other circumstances, is produced when the charge is increased with the same weight of projectile. In this case the projectile has to traverse a greater length of bore before the same relief due to expansion is attained. The higher pressures which consequently rule react upon the rate of combustion of the powder, and again a somewhat higher energy is obtained.

But these increased effects, of course, correspond to an increased initial tension of the powder-gases; but, especially with the smaller guns, a very great difference in the realised energy may arise from other causes. Thus, it having been found that with certain breech-loading guns a superior effect was attained by substituting copper rings for lead coating, it was assumed that the cause of this superiority was due to the less friction of the copper rings in the passage of the shot up the bore. But it occurred to one of us that the superior effect was in all probability not due to less friction, and the following experiments were made :—

Three rounds were fired from a 12-centimetre B.L. gun with 7 lbs. R. L. G. powder and the ordinary service lead-coated shot. The energy realised per lb. of powder was 80·65 foot-tons.

Three more rounds were fired with the lead considerably reduced, and so as barely to fill the grooves. The mean energy realised per lb. was 78·68 foot-tons, thus showing that no superior effect but the reverse was thereby obtained.

Two rounds were then fired with shell fitted with copper rings. The energy obtained was 82 foot-tons per lb., and the gain was real, but the chamber pressure ran up from a mean of 16·8 tons on the square inch to a mean of 18·6 tons; thus showing that, at all events in great measure, the increased effect is caused not by the copper bands giving rise to less loss by friction, but to the fact that the increased difficulty of forcing the copper bands into the grooves permits the powder to become fully burned at an earlier point in the bore, and thus an increased effect from the powder is realised.

But to show the effect of a greater or less degree of retention of the shot in its chamber in as clear a light as possible, the following experiments were made. Four projectiles for a 12-centimetre B.L. gun were manufactured of precisely the same weight, and which differed from one another in the following respect only: that two of these were fitted with a rotating gas-check of such a form that a high pressure would be necessary to force the projectile into the bore; the two others being fitted with gas-checks of a form such that a comparatively feeble pressure only would be requisite. The copper surfaces in contact with the bore were the same in each case.

Two rounds, one with each form of gas-check, were then fired with a charge of 7 lbs. of R. L. G. powder, every condition, except as noted, being precisely the same; the velocities with the two forms were respectively 1609 feet per second and 1512 feet per second, giving rise to 82·04 and 72·44 foot-tons per lb. of powder. The chamber pressures were respectively 15·2 and 12·0* tons per square inch. Two further rounds were then fired with charges of $7\frac{1}{2}$ lbs. R. L. G., when velocities of 1644 and 1544 feet per second, or energies per lb. of 79·94 and 70·51 foot-tons were respectively obtained, the chamber pressures in this case being 16·4 and 14·1 tons per square inch.

These experiments prove in the most complete manner that although there may be, and doubtless is, some difference in the amount of friction due to the employment of lead or copper as the driving or rotating material, that difference is perfectly insignificant when compared to the alteration in energy due to the projectile

* The figures given denote the pressures on the bottom of the chamber and the base of the projectile respectively. The pressures are given as observed, but that on the base of the projectile requires an addition not generally made in actual practice.

being more or less retained in its initial position, and thus permitting the powder to be consumed earlier and in a more complete manner.

In cases where the projectile has been removed for a considerable distance from the charge, that is, when there is a considerable air space between the charge and the projectile, it has been found that the energy developed in the projectile is materially higher than that due to the expansion of the powder-gases through the space traversed by the projectile, and the cause of this appears to us clear. When the charge is ignited at one end of the bore and the ignited products have to travel a considerable distance before striking the projectile, these ignited products possess considerable energy, and a portion of this energy will be communicated to the projectile by direct impact.

With the great lengths of charges used in the larger guns of the present day, some action of this sort doubtless, under ordinary circumstances, frequently happens, thus giving rise to somewhat more energy in the projectile than that due to the expansion of the gases from their initial density in the powder chamber to their final density when the projectile reaches the muzzle of the gun.*

A considerable number of rounds have been fired from small guns with mining powder. The particular powder of which the analysis is given in this memoir generated an energy differing but little from those obtained with R. L. G. under like conditions. Another sample of mining powder, however, differing from the first sample in containing a higher proportion of saltpetre, generated an energy higher than did any of the R. L. G. powders with which it was compared. This last powder, we may remark, was that which gave the pressure of 44 tons on the square inch when fired in an absolutely close vessel, with a gravimetric density of unity.

The Spanish spherical pellet powder generated rather less energy

* As bearing upon the energy which is usually assigned to a projectile, we may remark that it is customary in correcting the measured to the muzzle velocity to assume that the loss due to the resistance of the air has accrued from the instant the shot quitted the muzzle. But, especially with the large charges and high-muzzle pressures now employed, we believe this rule should be greatly modified.

For a considerable distance from the muzzle of the gun the projectile will be moving in an atmosphere with a velocity higher than its own, and for some short distance it appears to us probable that its velocity may be receiving an appreciable increase. As corroborative of our views, we may note the great indications of pressure upon gas-checks on the projectiles after these last are released from the support of the bore. Also the fact that when the muzzle velocities calculated from data measured inside the bore were compared with those calculated from the data measured outside, the latter were in all cases somewhat higher.

than did the mining powder, but in neither powder did the realised effect vary more from that generated by the normal service Waltham-Abbey powders than do occasional samples of these last — a sufficiently curious result, as we have already remarked, when the differences in the composition and the great differences in the decomposition of the various powders are taken into account.

The same remarks as to energy apply generally to the small-grained powders.

These, indeed, cannot be fired satisfactorily without special arrangements in very large charges, chiefly, among other reasons, from their tendency to cake under the pressure of the first ignited portion; but for smaller charges the tables in this memoir alike apply.

Of course, were similar weights of pebble, R. L. G., and F. G. fired in the same gun, the gun being supposed to be of small calibre, the energy realised by the F. G. would be greater than that realised by R. L. G., and still greater than that realised by pebble, on account of its much more rapid combustion. The maximum pressures developed in the bore would correspond with the energies realised.

When the maximum chamber pressure as well as the energy developed by a given charge in a given gun are known, we are able from Table 10 to fix very approximately the position of the shot in the bore when the combustion of the charge may practically be considered to be effected. Thus, if with a given energy in the projectile it is found that the maximum chamber pressure is 3118 atmospheres (20·46 tons on the square inch), we learn from Table 10 that this tension corresponds to a density of the products of combustion of ·70; and hence the charge may be supposed to be practically consumed when the projectile is in such a position in the bore that the products had this mean density. Again, if the observed pressure was 2400 atmospheres (15·73 tons per square inch), the same table shows us that, when this pressure is reached, the position of the projectile in the bore corresponds to a density of charge of ·60.

It will be gathered from what has just been said, that, with a little experience, if the factor of effect and maximum chamber pressure in any gun be known, the behaviour of the same powder in other guns, or in the same gun with other charges or weights of shot, can be anticipated. It was the consideration of the results embodied in Tables 10 and 11 that allowed the high energies (more than

twice as great as those obtained from the same calibres a few years back) to be predicted and realised; to be realised, also, with less strain to the gun than when much smaller charges were fired, without attention being paid to the all-important point of the density of the products of explosion at the moment when such explosion may be considered to be completed.

It will readily be understood from our remarks upon Table 11, that, to the artillerist, two descriptions of factors of effect are useful. One of these factors is employed to give the ratio between the work actually realised in a given gun, and the maximum work attainable by the charge (its gravimetric density being supposed to be unity). The value of this factor shows whether or not the charge is economically employed. The other factor is employed to denote the ratio between the work actually realised and the maximum work realisable by the charge, in expanding from the gravimetric density of the powder chamber to the mean density of the products of explosion, at the moment when the projectile leaves the muzzle of the gun.

With respect to the first class of factors, it would obviously be difficult to lay down general rules. The value of the factor depends mainly upon the gravimetric density of the charge, but we may remark that, in the most modern guns, even with the advantage they possess of great absolute length, the powder is very uneconomically burned. With the very high charges and consequent small number of expansions, with the low gravimetric density also of the charge, the realised energy per pound of powder is necessarily much lower than was the case with the older guns.

The same difficulty does not exist with regard to the second class of factors of effect. With respect to these, it may be enough to state that, in the smaller guns with R. L. G. powder, the factors of effect vary with a mild brand of powder from ·71 to ·76; with a specially violent brand, from ·82 to ·89, the variations being chiefly dependent upon the principles we have already explained.

In 6-inch guns, firing pebble-powder of the normal quality, the factors of effect vary from ·75 to ·82; and, as the calibres of the guns are increased, the factors of effect likewise gradually increase, until, in the 80- and 100-ton guns, factors of from ·89 to ·96 have usually been reached.

In concluding this memoir, we desire to remark that, although the agreement between the results of the long and laborious series of experiments and calculations which we now bring to a close have

far exceeded the expectations we had formed when we commenced our task, it would yet be idle to suppose that many of our deductions, referring as they do to temperatures and tensions far above the range of ordinary research, will not require some subsequent correction.

But although certain minor points may, as we have said, require considerable correction, we have little doubt that the main theories upon which we insist—confirmed, as they are, by experiments made or facts obtained under an almost infinite variety of circumstances—must be accepted as very approximately correct. It is satisfactory to find that the laws which rule the tensions and temperatures of gases under ordinary circumstances do not lose their physical significance, but are still approximately applicable at the high temperatures and pressures we have been considering.

At all events, whether we are right or wrong in taking this view, it appears to us certain that the rules and tables we have laid down, based on our analyses, experiments, and calculations, may for all practical purposes be accepted as correct, and may, bearing in mind the restrictions to which we have referred in this memoir, be applied to nearly every question of internal ballistics.

Memorandum showing the elementary substances found in the products of explosion, and existing in the powder before combustion.

Experiment 8.—102·77 grms. pebble, density = ·1.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	56·950	45·820
„ gas . .	58·411	44·359
„ mean . .	57·680	45·090

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	9·518	1·294	·153	22·298	11·827	
Solid state . .	30·039	2·803	7·227	·008	17·517	·086	
Total found .	30·039	12·321	8·521	·161	39·815	11·913	
Originally in powder .	29·660	12·456	10·349	·534	38·720	12·160	
Difference . .	+ ·379	− ·135	− 1·828	− ·373	+ 1·092	− ·247	

Oxygen in hyposulphite, 3·013 grms.

Experiment 7.—204·117 grms. pebble, density = ·2.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	111·271	92·846
„ gas . .	117·195	86·922
„ mean . .	114·233	89·844

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	19·06	3·53	·41	44·04	22·84	
Solid state . .	60·47	5·73	18·19	·01	29·74	·05	
Total found .	60·47	24·79	21·72	·42	73·78	22·89	
Originally in powder . .	58·91	24·74	20·56	1·06	76·58	23·01	
Difference . .	+1·56	+0·05	+1·16	− ·64	−2·80	−0·12	

Oxygen in hyposulphite, 1·070 grm.

Experiment 9.—306·175 grms. pebble, density = ·3.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	167·338	138·837
„ gas . .	174·011	132·164
„ mean . .	170·674	135·501

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	29·119	3·596	·442	67·927	34·417	
Solid state . .	90·126	8·904	26·166	·024	45·246	·208	
Total found .	90·126	38·023	29·762	·466	113·173	34·625	
Originally in powder . .	88·362	37·108	30·832	1·592	114·771	34·006	
Difference . .	−1·764	+0·915	−1·070	−1·126	−1·598	+0·619	

Oxygen in hyposulphite, 1·858 grm.

Experiment 12.—411·085 grms. pebble, density = ·4.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solids . .	237·717	173·368
" gas . .	230·767	180·318
" mean . .	234·242	176·843

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	38·314	2·712	·466	90·344	45·007	
Solid state . .	116·983	11·342	39·047	·013	64·703	·262	
Total found .	116·983	49·656	41·759	·479	155·047	45·269	
Originally in powder . .	118·639	49·824	41·396	2·138	154·058	45·235	
Difference . .	−1·656	−0·168	+·363	−1·659	+·989	+·034	

Oxygen in hyposulphite, 8·311 grms.

Experiment 14.—513·856 grms. pebble, density = ·5.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solids . .	278·232	235·624
" gas . .	288·739	225·117
" mean . .	283·485	230·370

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	49·715	4·073	·676	117·361	58·520	
Solid state . .	151·125	13·957	45·428	·018	72·595	·361	
Total found .	151·125	63·672	49·501	·694	189·956	58·881	
Originally in powder . .	148·299	62·279	51·745	2·672	192·505	56·244	
Difference . .	+2·826	+1·393	−2·244	−1·978	−2·549	+2·637	

Oxygen in hyposulphite, 4·372 grms.

Experiment 37.—295·488 grms. pebble, density = ·6.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	167·161	128·327
„ gas . .	166·076	129·412
„ mean . .	166·618	128·870

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	27·874	2·608	·398	65·580	32·410	
Solid state . .	85·001	8·424	26·806	·008	45·911	·468	
Total found .	85·001	36·298	29·414	·406	111·491	32·878	
Originally in powder . .	85·277	35·813	29·756	1·536	110·672	32·254	
Difference . .	−0·276	+0·485	−0·342	−1·130	+0·819	+0·624	

Oxygen in hyposulphite, 4·178 grms.

Experiment 38.—344·736 grms. pebble, density = ·70.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	202·460	142·276
„ gas . .	192·885	151·851
„ mean . .	197·673	147·063

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	31·133	4·193	·484	74·178	37·075	
Solid state . .	97·174	8·742	31·291	·009	60·143	·314	
Total found .	97·174	39·875	35·484	·493	134·321	37·389	
Originally in powder . .	99·491	41·782	34·715	1·793	129·060	37·413	
Difference . .	− ·317	−1·907	+ ·709	−1·300	+5·261	− ·024	

Oxygen in hyposulphite, 16·030 grms.

Experiment 43 (76).—393·984 grms. pebble, density = ·8.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	229·932	164·052
„ gas . .	219·181	174·803
„ mean . .	224·557	169·427

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	36·157	2·965	·402	86·801	43·102	
Solid state . .	111·046	11·647	34·704	·015	66·653	·490	
Total found .	111·046	47·804	37·669	·417	153·454	43·592	
Originally in powder . .	113·704	47·751	39·674	2·049	147·519	42·801	
Difference . .	− 2·658	+ ·053	− 2·005	− 1·632	+ 5·935	+ ·791	

Oxygen in hyposulphite, 11·708 grms.

Experiment 77.—417·31 grms. pebble, density = ·9.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	246·150	171·160
„ gas . .	232·380	184·930
„ mean . .	239·260	178·050

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	37·765	3·385	·547	90·866	45·492	
Solid state . .	117·064	13·570	37·799	·023	70·127	·676	
Total found .	117·064	51·335	41·184	·570	160·993	46·168	
Originally in powder . .	120·436	50·578	42·023	2·170	156·237	45·306	
Difference . .	− 3·372	+ ·757	− ·839	− 1·600	+ 4·756	+ ·862	

Oxygen in hyposulphite, 8·001 grms.

Experiment 1.—90·719 grms. R. L. G., density = ·1.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	52·256	38·463
" gas . .	51·565	39·154
" mean . .	51·910	38·809

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	7·648	1·421	·149	18·698	10·894	
Solid state . .	26·113	2·747	6·774	·003	16·222	·051	
Total found .	26·113	10·395	8·195	·152	34·920	10·945	1st analysis of powder top of barrel.
Originally in powder . .	26·299	9·852	9·344	·490	34·698	11·149	
Difference . .	− ·186	+ ·543	− 1·149	− ·338	+ ·222	− ·204	

Oxygen in hyposulphite, 2·665 grms.

Experiment 3.—190·538 grms. R. L. G., density = ·2.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	108·556	81·982
" gas . .	109·503	81·035
" mean . .	109·030	81·508

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	16·256	2·669	·289	39·397	22·896	
Solid state . .	55·479	5·222	16·191	·005	32·037	·100	1st analysis
Total found .	55·479	21·478	18·860	·294	71·434	22·996	
Originally in powder . .	55·237	20·692	19·625	1·029	72·559	22·169	
Difference . .	+ ·242	+ ·786	− ·765	− ·735	− 1·125	+ ·827	

Oxygen in hyposulphite, 1·580 grm.

Experiment 4.—285·833 grms. R. L. G., density = ·3.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	165·992	119·841
" gas . .	163·174	122·659
" mean . .	164·583	121·250

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	25·142	3·423	·421	60·582	31·683	1st analysis
Solid state . .	82·167	7·521	24·770	·005	50·068	·053	
Total found . .	82·167	32·663	28·193	·426	110·650	31·736	
Originally in powder . .	82·863	31·041	29·441	1·543	108·674	32·756	
Difference . .	− ·696	+1·622	−1·248	−1·117	+1·976	−1·020	

Oxygen in hyposulphite, 5·330 grms.

Experiment 11.—381·091 grms. R. L. G., density = ·4.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	224·951	156·140
" gas . .	216·358	164·753
" mean . .	220·655	160·436

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	33·338	2·793	·451	80·520	43·334	1st analysis
Solid state . .	108·521	9·400	33·047	·007	69·500	·180	
Total found .	108·521	42·738	35·840	·458	150·020	43·514	
Originally in powder . .	110·478	41·386	39·252	2·058	144·859	43·278	
Difference . .	−1·957	+1·352	−3·412	−1·600	+5·161	+ ·236	

Oxygen in hyposulphite, 13·379 grms.

Experiment 70.—246·286 grms. R. L. G., density = ·5.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	143·997	102·289
" gas . .	141·824	104·462
" mean . .	142·910	103·376

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	23·215	1·537	·373	53·089	25·162	
Solid state . .	70·862	7·610	22·013	·011	42·133	·281	
Total found .	70·862	30·825	23·550	·384	95·222	25·443	
Originally in powder . .	70·906	30·535	24·917	1·278	90·768	27·873	
Difference . .	− ·044	+ ·290	−1·367	− ·894	+4·454	−2·430	

Oxygen in hyposulphite, 9·122 grms.

Experiment 39.—295·483 grms. R. L. G., density = ·6.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	167·871	127·612
" gas . .	168·697	126·786
" mean . .	168·284	127·199

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	27·734	1·856	·020	65·477	31·812	*N.B.*—2nd analysis taken.
Solid state . .	85·451	9·421	26·182	·015	47·016	·199	
Total found .	85·451	37·155	28·038	·335	112·493	32·011	
Originally in powder . .	85·070	36·634	29·894	1·534	108·131	32·766	
Difference . .	+ ·381	+ ·521	−1·856	−1·199	+4·362	− ·755	

Oxygen in hyposulphite, 2·748 grms.

Experiment 96.—295·488 grms. R. L. G., density = ·6.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	169·403	126·085
" gas . .	169·256	126·232
" mean . .	169·330	126·158

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	26·454	4·938	·511	61·681	32·574	2nd analysis
Solid state . .	85·031	9·694	25·771	·012	48·514	·308	
Total found .	85·031	36·148	30·709	·523	110·195	32·882	
Originally in powder . .	85·071	36·635	29·895	1·534	108·870	33·250	
Difference . .	− ·040	− ·487	+ ·814	− 1·011	+ 1·325	− ·368	

Oxygen in hyposulphite, 2·940 grms.

Experiment 41.—344·736 grms. R. L. G., density = ·7.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	201·915	142·821
" gas . .	194·931	149·805
" mean . .	198·423	146·313

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	31·195	3·745	·642	74·051	36·681	2nd analysis
Solid state . .	98·211	10·545	30·085	·013	59·083	·486	
Total found .	98·211	41·740	33·830	·655	133·134	37·167	
Originally in powder . .	99·249	42·740	34·877	1·787	126·987	38·803	
Difference . .	− 1·038	− 1·000	− 1·047	− 1·132	+ 6·147	− 1·636	

Oxygen in hyposulphite, 9·300 grms.

Experiment 44.—393·978 grms. R. L. G., density = ·8.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	221·009	172·969
„ gas . .	231·376	162·602
„ mean . .	226·192	167·785

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state . .	...	36·327	2·338	·452	86·473	42·195	2nd analysis
Solid state . .	111·655	13·185	39·264	·021	61·613	·452	
Total found . .	111·655	49·512	41·602	·473	148·086	42·647	
Originally in powder . .	113·426	48·845	39·859	2·045	145·103	42·987	
Difference . .	−1·771	+·667	+1·743	−1·572	+2·983	−·340	

Oxygen in hyposulphite, 1·761 grm.

Experiment 68.—443·23 grms. R. L. G., density = ·9.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	257·858	185·372
„ gas . .	248·696	194·534
„ mean . .	253·277	189·953

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state . .	...	40·551	3·199	·500	97·626	48·077	2nd analysis
Solid state . .	126·402	14·635	40·142	·031	71·412	·643	
Total found . .	126·402	55·186	43·341	·531	169·038	48·720	
Originally in powder . .	127·606	54·952	44·842	2·300	163·233	49·735	
Difference . .	−1·204	+·234	−1·501	−1·769	+5·805	−1·015	

Oxygen in hyposulphite, 5·490 grms.

Experiment 16.—102·771 grms. F. G., density = ·10.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	55·762	47·009
" gas . .	61·736	41·038
" mean . .	58·749	44·022

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	9·436	0·928	·164	21·784	11·710	
Solid state . .	30·905	2·524	7·721	·003	18·028	·068	
Total found .	30·905	11·960	8·149	·167	39·812	11·778	
Originally in powder . .	29·331	11·675	10·380	·668	39·795	11·927	
Difference . .	+1·574	+ ·285	−2·231	− ·501	+ ·017	− ·149	

Oxygen in hyposulphite, 3·518 grms.

Experiment 17.—205·542 grms. F. G., density = ·2.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	116·719	88·823
" gas . .	122·390	83·152
" mean . .	119·544	85·987

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	17·770	2·977	·393	42·430	22·417	
Solid state . .	60·080	6·202	16·091	·015	37·099	·068	
Total found .	60·080	23·972	19·068	·408	79·527	22·485	
Originally in powder . .	58·662	23·349	20·760	1·336	79·281	23·055	
Difference . .	+1·413	+ ·623	−1·692	− ·928	+ ·246	− ·570	

Oxygen in hyposulphite, 1·597 grm.

Experiment 18.—308·32 grms. F. G., density = ·3.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	177·44	130·88
„ gas . .	181·80	126·52
„ mean . .	179·62	128·70

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	27·055	2·579	·419	65·764	32·883	
Solid state . .	89·076	7·219	26·863	·002	56·388	·072	
Total found .	89·076	34·274	29·442	·421	122·152	32·955	
Originally in powder . .	89·994	35·025	31·140	2·004	118·750	33·088	
Difference . .	− ·918	− ·751	−1·698	−1·583	+3·402	− ·133	

Oxygen in hyposulphite, 12·484 grms.

Experiment 19.—411·085 grms. F. G., density = ·4.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	237·880	173·210
„ gas . .	240·970	170·116
„ mean . .	239·430	171·660

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	36·039	3·086	·519	88·006	44·015	
Solid state . .	118·118	9·382	37·849	·008	73·990	·086	
Total found .	118·118	45·421	40·935	·527	161·996	44·101	
Originally in powder . .	117·325	46·700	41·520	2·672	158·294	45·030	
Difference . .	+ ·793	−1·279	− ·585	−2·145	+3·702	− ·929	

Oxygen in hyposulphite, 17·262 grms.

Experiment 75.—246·286 grms. F. G., density = ·5.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	141·760	104·526
,, gas . .	144·474	101·812
,, mean . .	143·117	103·169

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	21·526	2·049	·334	52·261	26·999	
Solid state . .	70·963	7·000	21·291	·009	43·768	·085	
Total found .	70·963	28·526	23·340	·343	96·029	27·084	
Originally in powder . .	70·290	27·978	24·875	1·601	94·805	26·849	
Difference . .	+ ·673	+ ·548	− 1·535	− 1·258	+ 1·224	+ ·235	

Oxygen in hyposulphite, 4·840 grms.

Experiment 40.—295·488 grms. F. G., density = ·6.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	170·268	125·220
,, gas . .	172·509	122·979
,, mean . .	171·388	124·099

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	25·770	2·511	·368	63·097	32·353	
Solid state . .	84·762	6·281	26·233	·002	53·973	·137	
Total found .	84·762	32·051	28·744	·370	117·070	32·490	
Originally in powder . .	84·332	33·567	29·844	1·921	113·765	32·106	
Difference . .	+ ·430	− 1·516	− 1·100	− 1·551	+ 3·305	+ ·384	

Oxygen in hyposulphite, 13·786 grms.

Experiment 42.—344·738 grms. F. G., density = ·7.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solids . .	200·191	144·547
„ gas . .	200·220	144·520
„ mean . .	200·210	144·533

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	29·628	2·614	·413	73·372	38·503	
Solid state . .	98·540	7·474	30·531	·112	63·417	·135	
Total found .	98·540	37·102	33·145	·525	136·789	38·638	
Originally in powder . .	98·388	39·162	34·819	2·241	132·644	37·357	
Difference . .	+ ·152	− 2·060	− 1·674	− 1·716	+ 4·145	+ 1·281	

Oxygen in hyposulphite, 16·182 grms.

Experiment 47.—393·987 grms. F. G., density = ·8.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solids . .	231·652	162·335
„ gas . .	229·392	164·595
„ mean . .	230·522	163·465

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	33·138	3·800	·492	81·851	44·184	
Solid state . .	111·893	8·830	36·136	·008	73·363	·292	
Total found .	111·893	41·968	39·936	·500	155·214	44·476	
Originally in powder . .	112·444	44·757	39·793	2·561	151·572	42·614	
Difference . .	− ·551	− 2·789	+ ·143	− 2·061	+ 3·642	+ 1·862	

Oxygen in hyposulphite, 20·106 grms.

Experiment 69.—443·230 grms. F. G., density = ·90.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	255·256	187·974
" gas . .	257·131	186·099
" mean . .	256·193	187·037

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	38·027	4·875	·545	94·624	48·966	
Solid state . .	127·001	11·372	38·012	·006	79·476	·327	
Total found .	127·001	49·399	42·887	·551	174·100	49·293	
Originally in powder . .	126·495	50·350	44·765	2·881	170·498	47·878	
Difference . .	+ ·506	− ·951	− 1·878	− 2·330	+ 3·602	+ 1·415	

Oxygen in hyposulphite, 16·702 grms.

Experiment 78.—344·738 grms. R. F. G., density = ·7.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	202·222	142·516
" gas . .	200·960	143·780
" mean . .	201·591	143·148

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	29·469	2·048	·346	72·664	38·621	
Solid state . .	99·765	10·360	29·551	·008	61·834	·073	
Total found .	99·765	39·829	31·599	·354	134·498	38·694	
Originally in powder . .	100·077	36·784	34·336	2·103	134·747	36·323	
Difference . .	− ·312	+ 3·045	− 2·737	− 1·749	− ·250	+ 2·371	

Oxygen in hyposulphite, 4·140 grms.

Experiment 79.—344·738 grms. Spanish, density = ·7.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	214·917	129·821
" gas . .	213·875	130·863
" mean . .	214·396	130·342

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	24·953	3·140	·288	64·032	37·930	
Solid state . .	100·418	6·545	38·338	·007	68·758	·330	
Total found .	100·418	31·498	41·478	·295	132·790	38·260	
Originally in powder . .	100·663	29·820	42·989	1·551	131·506	36·461	
Difference . .	− ·245	+1·678	−1·511	−1·256	+1·284	+1·799	

Oxygen in hyposulphite, 4·106 grms.

Experiment 196.—301·315 grms. Curtis and Harvey's No. 6, density = ·3.

	Calculated solid products.	Calculated gaseous products.
	Grms.	Grms.
From analysis of solids . .	168·827	128·963
" gas . .	180·818	116·972
" mean . .	174·823	122·967

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	25·389	2·337	·725	60·639	33·877	
Solid state . .	90·017	8·918	24·324	·013	51·435	·116	
Total found .	90·017	34·307	26·661	·738	112·074	33·993	
Originally in powder . .	86·929	32·120	31·427	1·567	113·687	31·156	
Difference . .	+3·088	+2·187	−4·766	− ·829	−1·613	+2·837	

Oxygen in hyposulphite, 1·731 grm.

Experiment 194.—301·315 grms. mining powder, density = ·3.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solids . .	142·743	153·921
" gas . .	143·895	152·569
" mean . .	143·319	153·145

Elements in—	K.	C.	S.	H.	O.	N.	Remarks.
Gaseous state .	...	39·601	10·909	1·714	75·330	25·591	
Solid state . .	70·596	11·801	35·901	·205	23·488	1·328	
Total found .	70·596	51·402	46·810	1·919	98·818	26·919	
Originally in powder . .	72·014	54·026	45·378	1·989	95·336	25·943	
Difference . .	−1·418	−2·624	+1·432	−·070	+3·482	+·976	

Oxygen in hyposulphite, 2·062 grms.

Abstract of Experiments

In this abstract the following abbreviations are used:—

δ, to represent the mean density of the products of explosion; A, the area of the piston of the crusher-gauge; a, the sectional area of the copper cylinder.

Experiment 96.—4560 grs. (295·49 grms.) R. L. G.; this experiment is No. 39 repeated. On opening cylinder, appearances as usual—colour of fracture, a dark bluish grey; surface not smooth but wavy; tears remained adhering to the side, and the usual sooty deposit observed.

δ.	A.	a.	Crush.	Pressure.
·57	·0833	·0417	·134	14·32 tons per square inch.

Experiment 121.—Fired 5960 grs. (386·21 grms.) R. L. G. in large cylinder. Density ·4.

On opening, appearances much as usual. Fracture, slaty grey with yellowish portions. Divided deposit into two portions, top and bottom. Bottom decidedly more yellow than the top. Divided again top and bottom portions into two parts, one bottled and sealed with as little exposure to the air as possible, the other ground and freely exposed to the air for 48 hours.

The ground portion heated but slightly, the bottom portion show-

ing this tendency in the highest degree, but the heating was on the whole very abnormally low.

During exposure the colour of the ground deposit became considerably lighter.

Experiment 122.—Fired 5960 grs. (386·21 grms.) pebble in large cylinder. Density ·4.

On opening the cylinder, observed that the deposit was lighter in colour than in the case of the R. L. G. The fracture was also different, being lighter, and having several isolated portions yellow or greenish yellow.

Divided, as in last experiment, the deposit into top and bottom, a portion of each being bottled with as little exposure as possible, and a portion of each being finely ground and exposed to the atmosphere for about 48 hours.

The bottom part of the deposit was lighter and yellower than the top portion.

The top ground deposit began to heat when placed on the paper, the deposit on the apex and in the interior, where the greatest heat prevailed, changing rapidly to a light sulphury yellow with a tinge of green.

It attained its greatest heat in about 10 minutes, and in about 15 minutes later was not *hot* to the hand.

The bottom ground portion exhibited the tendency to heat in a much higher degree than the top portion, commencing to heat immediately; the colour of the residue darkening, while an orange coloured deposit formed on the surface.

During the exhibition of heat, the ground residue smoked considerably, the orange colour on the surface was doubtless due to this vapour.

The smell was very peculiar, SH_2 was quite perceptible, but was not the dominant odour.

The maximum temperature occurred at about twenty minutes after exposure, and a thermometer placed in the centre showed a temperature of over 600° Fahr. (310°·6 Cent.). The temperature might have been somewhat higher, as the thermometer had to be withdrawn for fear of fracture.

The paper was burned through on which the deposit was placed. After half an hour the deposit began to cool rapidly.

It is to be noticed that the heat appears to play an important part in the changes which take place, as it was observed that the

residue at the base of the cone remained unchanged in appearance, although more exposed to the action of the air than other portions.

It may also be noted that after the residue has gone through this heating process, the physical characteristics are considerably changed.

When taken out of the exploding-vessel the residue is always difficult to pound in the mortar, being somewhat unctuous or greasy to the touch, but after the development of the heating phase it becomes crisp and powdery.

Determinations of heat absorbed by calorimeter. Temperature of room, 62°.

Experiment 129.

	Fahr.
Temperature of calorimeter	58°·95
„ 30,000 grs. water	79°·0
Water poured into calorimeter.	
After 1 minute, temperature	78°·24
„ 2 „ „	78°·22
„ 4 „ „	78°·10
„ 6 „ „	78°·00

Hence loss of heat 0°·76 Fahr. in one minute.

Experiment 130.

	Fahr.
Temperature of calorimeter	60°·2
„ water	77°·6
After 1 minute, temperature	76°·8
„ 2 „ „	76°·7
„ 3 „ „	76°·62
„ 4 „ „	76°·6
„ 6 „ „	76°·5

Hence loss of heat 0°·8 Fahr. in one minute.

Experiment 131.

	Fahr.
Temperature of calorimeter	61°·08
„ water	71°·4
After 1 minute, temperature	71°·0
„ 3 „ „	71°·0
„ 5 „ „	70°·95

Loss of heat 0°·4 Fahr. in one minute.

Experiment 132.

	Fahr.
Temperature of calorimeter	62°·1
„ water	70°·8
After 1 minute, temperature	70°·4
„ 2 „ „	70°·4

Loss of heat 0°·4 Fahr. in one minute.

Experiment 133.

	Fahr.
Temperature of calorimeter	62°·6
„ 30,000 grs. water	70°·6
Water poured into calorimeter.	
After 1 minute, temperature	70°·25
„ 2 „ „	70°·2

Loss of heat 0°·35 Fahr. in one minute.

Experiment 134.

	Fahr.
Temperature of calorimeter	63°·45
„ water	70°·2
After 1 minute, temperature	70°·0
„ 2 „ „	70°·0

Loss of heat 0°·2 Fahr. in one minute.

Experiment 135.

	Fahr.
Temperature of calorimeter	64°·05
„ water	70°·0
After 1 minute, temperature	69°·82
„ 2 „ „	69°·8

Hence loss of heat 0°·18 Fahr. in one minute.

From the above and similar experiments the following table of loss of heat (the difference of temperature between water and original state of calorimeter being taken as argument) was arranged.

For 30,000 grs. water: Difference of temperature. Fahr.	Loss of heat. Fahr.	For large explosion-vessel. Calorimeter with 25,000 grs. of water: Loss of heat. Fahr.
2°	0°·08	0°·13
4°	0°·16	0°·26
6°	0°·24	0°·39
8°	0°·32	0°·52
10°	0°·40	0°·65
12°	0°·48	0°·78
14°	0°·56	0°·91
16°	0°·64	1°·04
18°	0°·72	1°·18
20°	0°·80	1°·31
22°	0°·88	1°·44
24°	0°·96	1°·57
26°	1°·04	1°·70
27°	...	1°·77
28°	...	1°·83
29°	...	1°·90

Experiments for the determination of the specific heats of the vessels used for determining the heat generated by explosion.

In all cases the vessel was boiled, and then kept for five minutes suspended in the escaping steam; it was then transferred to the calorimeter containing 30,000 grs. of distilled water.

Experiment 141.—Weight of vessel, 21,311·6 grs. (1381·0 grms.).

	Fahr.
Temperature of air	58°·8
„ steam	211°·65
„ calorimeter before immersion of vessel	58°·88
„ calorimeter after thermometer became stationary	70°·08
Loss of heat in vessel . 211°·65 − 70°·08 + 0°·2	= 141°·77
Gain of heat in water . . . . 11°·2 + 0°·44 =	11°·64

Hence specific heat of vessel = ·1156.

Experiment 142.—The same vessel.

	Fahr.
Temperature of air	59°·0
„ steam	211°·65
„ calorimeter before experiment .	62°·21
„ „ after „ . . .	73°·20
Loss of heat in vessel . 211°·65 − 73°·20 + 0°·2	= 138°·65
Gain of heat in water . . . . 10°·99 + 0°·44 =	11°·43

Hence specific heat of vessel = ·1158.

Experiment 143.—The same vessel.

	Fahr.
Temperature of air	60°·20
„ steam	212°·20
„ calorimeter before experiment .	61°·11
„ „ after „ . . .	72°·20
Loss of heat in vessel . 212°·20 − 72°·20 + 0°·20	= 140°·20
Gain of heat in water . . . . 11°·09 + 0°·44 =	11°·53

Hence specific heat of vessel = ·1155.

Experiment 144.—The same vessel.

	Fahr.
Temperature of air	60°·20
„ steam	212°·10
„ calorimeter before experiment . .	65°·10
„ „ after „ . . .	75°·95
Loss of heat in vessel . 212°·20 − 75°·95 + 0°·2	= 136°·45
Gain of heat in water . . . . 10°·85 + 0°·44 =	11°·29

Hence specific heat of vessel = ·1163.

Hence mean specific heat of vessel from four experiments = ·1158.

Experiment 167.—Weight of vessel, 52,931·6 grs. (3430 grms.).

		Fahr.
Temperature of air	. . . .	60°·0
„ steam	. . . .	211°·14
„ calorimeter before experiment	.	55°·75
„ „ after „	. . .	84°·52
Loss of heat in vessel	. 211°·14 − 84°·52 + 0°·2	= 126°·82
Gain of heat in water (25,000 grs.)	28°·77 + 1°·86 =	30°·63

Hence specific heat of vessel = ·1140.

Experiment 168.—The same vessel.

		Fahr.
Temperature of air	. . . .	62°·0
„ steam	. . . .	211°·14
„ calorimeter before experiment	.	55°·48
„ „ after „	. . .	84°·10
Loss of heat in vessel	. 211°·14 − 84°·10 + 0°·2	= 127°·24
Gain of heat in water	. . . 28°·60 + 1°·85 =	30°·40

Hence specific heat of vessel = ·1132.

Experiment 169.—The same vessel.

		Fahr.
Temperature of air	. . . .	62°·0
„ steam	. . . .	211°·14
„ calorimeter before experiment	.	55·°55
„ „ after „	. . .	84°·30
Loss of heat in vessel	. 211°·14 − 84°·30 + 0°·2	= 127°·04
Gain of heat in water	. . . 28°·75 + 1°·86 =	30°·61

Hence specific heat of vessel = ·1138.

Hence mean specific heat of vessel from three experiments = ·1137.

Determination of heat evolved by the various powders.

A.—Small explosion-vessel.

		Grs.
Weight of water, 30,000 grs.	. equivalent in water	30,000·0
„ explosion-vessel, 21,311·6 grs.	„ „	2,465·8
„ powder products . . .	„ „	28·5
Equivalent in water, of contents of calorimeter	. . .	32,494·3
When 200 grs. of powder used, the equivalent in water of the contents of the calorimeter is	. . . . .	32,503·8

Experiment 146.—Exploded 150 grs. Curtis and Harvey's No. 6.

		Fahr.
Temperature of calorimeter before explosion	. .	61°·50
„ „ after „	. . .	67°·78
Hence difference	. . . . . 6°·28 + 0°·24 =	6°·52

Hence heat evolved = 784·0 grm.-units Cent.

Experiment 147.—Exploded 150 grs. Spanish.

		Fahr.
Temperature of calorimeter before explosion	. .	65°·10
„ „ after „	. .	71°·20
Hence difference	. 6°·10 + 0°·24 =	6°·34

Hence heat evolved = 762·5 grm.-units Cent.

Experiment 148.—Exploded 150 grs. R. L. G.

		Fahr.
Temperature of calorimeter before explosion	. .	56°·28
„ „ after „	. .	62°·07
Hence difference	. 5°·79 + 0°·24 =	6°·03

Hence heat evolved = 725·1 grm.-units Cent.

Experiment 149.—Exploded 150 grs. pebble.

		Fahr.
Temperature of calorimeter before explosion	. .	60°·42
„ „ after „	. .	66°·10
Hence difference	. 5°·68 + 0°·24 =	5°·92

Hence heat evolved = 711·9 grm.-units Cent.

Experiment 150.—Exploded 150 grs. F. G.

		Fahr.
Temperature of calorimeter before explosion	. .	65°·16
„ „ after „	. .	70°·80
Hence difference	5°·64 + 0°·23 =	5°·87

Hence heat evolved = 706·45 grm.-units Cent.

Experiment 153.—With 200 grs. pebble.

Failure; the plug being spoiled by the explosion.

Experiment 154.—Exploded 150 grs. F. G.

		Fahr.
Temperature of calorimeter before explosion	. .	49°·55
„ „ after „	. .	55°·45
Hence difference	. 59°·0 + 0°·24 =	6°·14

Hence heat evolved = 738·9 grm.-units Cent.

Experiment 155.—Exploded 150 grs. R. L. G.

		Fahr.
Temperature of calorimeter before explosion	. .	86°·00
„ „ after „	. .	91°·73
Hence difference	. 5°·73 + 0°·24 =	5°·97

Hence heat evolved = 718·4 grm.-units Cent.

Experiment 156.—Exploded 150 grs. pebble.

		Fahr.
Temperature of calorimeter before explosion . .		56°·07
,, ,, after ,, . .		61°·95
Hence difference	$5°·87 + 0°·23 =$	6°·10

Hence heat evolved = 734·1 grm.-units Cent.

Experiment 157.—Exploded 150 grs. Spanish.

		Fahr.
Temperature of calorimeter before explosion . .		56°·90
,, ,, after ,, . .		63°·06
Hence difference	$6°·16 + 0°·25 =$	6°·41

Hence heat evolved = 771·4 grm.-units Cent.

Experiment 158.—Exploded 150 grs. Curtis and Harvey's No. 6.

		Fahr.
Temperature of calorimeter before explosion . .		57°·92
,, ,, after ,, . .		63°·87
Hence difference	$5°·95 + 0°·24 =$	6°·19

Hence heat evolved = 744·9 grm.-units Cent.

Experiment 159.—Exploded 150 grs. mining.

		Fahr.
Temperature of calorimeter before explosion . .		58°·50
,, ,, after ,, . .		62°·54
Hence difference	$4°·04 + 0°·16 =$	4°·02

Hence heat evolved = 505·5 grm.-units Cent.

Experiment 160.—Exploded 150 grs. R. L. G.

		Fahr.
Temperature of calorimeter before explosion . .		62°·42
,, ,, after ,, . .		68°·06
Hence difference	$5°·64 + 0°·24 =$	5°·88

Hence heat evolved = 707·5 grm.-units Cent.

Experiment 161.—Exploded 150 grs. pebble.

		Fahr.
Temperature of calorimeter before explosion . .		49°·05
,, ,, after ,, . .		54°·59
Hence difference	$5°·54 + 0°·23 =$	5°·77

Hence heat evolved = 694·4 grm.-units Cent.

Experiment 162.—Exploded 150 grs. mining.

		Fahr.
Temperature of calorimeter before explosion . .		56°·80
,, ,, after ,, . .		60°·82
Hence difference	$4°·02 + 0°·20 =$	4°·22

Hence heat evolved = 507·9 grm.-units Cent.

Experiment 163.—Exploded 150 grs. Curtis and Harvey's No. 6.

		Fahr.
Temperature of calorimeter before explosion	. .	52°·80
„ „ after „	. .	58°·65
Hence difference	. 5°·85 + 0°·24 =	6°·09

Hence heat evolved = 732·9 grm.-units Cent.

Experiment 164.—Exploded 150 grs. F. G.

		Fahr.
Temperature of calorimeter before explosion	. .	57°·42
„ „ after „	. .	63°·26
Hence difference	. 5°·84 + 0°·24 =	6°·08

Hence heat evolved = 731·7 grm.-units Cent.

Experiment 165.—Exploded 150 grs. Spanish.

		Fahr.
Temperature of calorimeter before explosion	. .	55°·70
„ „ after „	. .	61°·72
Hence difference	. 6°·02 + 0°·24 =	6°·26

Hence heat evolved = 753·4 grm.-units Cent.

Experiment 166.—Exploded 150 grs. pebble.

		Fahr.
Temperature of calorimeter before explosion	. .	61°·12
„ „ after „	. .	66°·80
Hence difference	. 5°·68 + 0°·22 =	5°·90

Hence heat evolved = 710·0 grm.-units Cent.

Experiment 151.—Exploded 200 grs. mining.

		Fahr.
Temperature of calorimeter before explosion	. .	60°·38
„ „ after „	. .	65°·87
Hence difference	. 5°·49 + 0°·22 =	5°·71

Hence heat evolved = 512·7 grm.-units Cent.

Experiment 152.—Exploded 200 grs. Curtis and Harvey's No. 6.

		Fahr.
Temperature of calorimeter before explosion	. .	64°·95
„ „ after „	. .	73°·00
Hence difference	. 8°·05 + 0°·32 =	8°·37

Hence heat evolved = 755·7 grm.-units Cent.

B.—Large explosion-vessel.

		Grs.
Weight of water, 25,000 grs. . .	equivalent in water	25,000·0
„ explosion-vessel, 52,931·6 grs. .	„ „	6,018·3
„ powder products, 400 grs. . .	„ „	76·0
Equivalent in water, of contents of calorimeter	. . .	31,094·3

Experiment 171.—Exploded 400 grs. pebble.

	Fahr.
Temperature of calorimeter before explosion . .	54°·38
" " after " . .	69°·43
Hence difference	15°·05 + 1°·24 = 16°·29

Hence heat evolved = 703·41 grm.-units Cent.

Experiment 172.—Exploded 400 grs. R. L. G.

	Fahr.
Temperature of calorimeter before explosion . .	57°·08
" " after " . .	72°·44
Hence difference	15°·36 + 1°·26 = 16°·62

Hence heat evolved = 717·7 grm.-units Cent.

Experiment 173.—Exploded 400 grs. R. L. G.

	Fahr.
Temperature of calorimeter before explosion . .	57°·22
" " after " . .	72°·74
Hence difference	15°·52 + 1°·26 = 16°·78

Hence heat evolved = 724·7 grm.-units Cent.

Experiment 174.—Exploded 400 grs. pebble.

	Fahr.
Temperature of calorimeter before explosion . .	57°·13
" " after " . .	72°·42
Hence difference	15°·29 + 1°·26 = 16°·55

Hence heat evolved = 714·7 grm.-units Cent.

Experiment 175.—Exploded 400 grs. pebble.

	Fahr.
Temperature of calorimeter before explosion . .	56°·40
" " after " . .	72°·00
Hence difference	15°·6 + 1°·27 = 16°·87

Hence heat evolved = 728·5 grm.-units Cent.

Experiment 176.—Exploded 400 grs. R. L. G.

	Fahr.
Temperature of calorimeter before explosion . .	67°·12
" " after " . .	82°·38
Hence difference	15°·26 + 1°·26 = 16°·52

Hence heat evolved = 713·4 grm.-units Cent.

Experiment 177.—Exploded 400 grs. mining.

	Fahr.
Temperature of calorimeter before explosion . .	53°·27
" " after " . .	64°·13
Hence difference	10°·86 + 0°·71 = 11°·57

Hence heat evolved = 499·65 grm.-units Cent.

Experiment 178.—Exploded 400 grs. mining.

		Fahr.
Temperature of calorimeter before explosion	. .	57°·25
" " after "	. .	68°·27
Hence difference	. . . .	11°·02 + 0°·72 = 11°·74

Hence heat evolved = 507·0 grm.-units Cent.

Experiment 179.—Exploded 400 grs. mining.

		Fahr.
Temperature of calorimeter before explosion	. .	64°·73
" " after "	. .	76°·03
Hence difference	. . . .	11°·30 + 0°·74 = 12°·04

Hence heat evolved = 520·0 grm.-units Cent.

Experiment 181.—Exploded 400 grs. Spanish.

		Fahr.
Temperature of calorimeter before explosion	. .	51°·62
" " after "	. .	67°·76
Hence difference	. . . .	16°·14 + 1°·32 = 17°·46

Hence heat evolved = 754·0 grm.-units Cent.

Experiment 182.—Exploded 400 grs. Spanish.

		Fahr.
Temperature of calorimeter before explosion	. .	66°·90
" " after "	. .	83°·21
Hence difference	. . . .	16°·31 + 1°·33 = 17°·64

Hence heat evolved = 761·8 grm.-units Cent.

Experiment 183.—Exploded 400 grs. special mining.

		Fahr.
Temperature of calorimeter before explosion	. .	52°·72
" " after "	. .	63°·58
Hence difference	. . . .	10°·86 + 0°·71 = 11°·57

Hence heat evolved = 499·65 grm.-units Cent.

Experiment 184.—Exploded 400 grs. Spanish.

		Fahr.
Temperature of calorimeter before explosion	. .	58°·52
" " after "	. .	75°·03
Hence difference	. . . .	16°·51 + 1°·35 = 17°·86

Hence heat evolved = 771·3 grm.-units Cent.

Experiment 185.—Exploded 400 grs. Curtis and Harvey's No. 6.

		Fahr.
Temperature of calorimeter before explosion	. .	53°·19
" " after "	. .	69°·26
Hence difference	. . . .	16°·07 + 1°·31 = 17°·38

Hence heat evolved = 750·6 grm.-units Cent.

Experiment 186.—Exploded 400 grs. Curtis and Harvey's No. 6.

	Fahr.
Temperature of calorimeter before explosion . .	55°·80
" " after " . .	72°·19
Hence difference . . . . . $16°·39+1°·33=$	17°·72

Hence heat evolved = 765·3 grm.-units Cent.

Experiment 187.—Exploded 400 grs. Curtis and Harvey's No. 6.

	Fahr.
Temperature of calorimeter before explosion . .	53°·48
" " after " . .	69°·58
Hence difference . . . . . $16°·10+1°·32=$	17°·42

Hence heat evolved = 752·3 grm.-units Cent.

Experiment 189.—Exploded 400 grs. F. G.

	Fahr.
Temperature of calorimeter before explosion . .	55°·61
" " after " . .	71°·26
Hence difference . . . . . $15°·65+1°·28=$	16°·93

Hence heat evolved = 731·1 grm.-units Cent.

Experiment 191.—Exploded 400 grs. F. G.

	Fahr.
Temperature of calorimeter before explosion . .	53°·04
" " after " . .	68°·49
Hence difference . . . . . $15°·45+1°·27=$	16°·72

Hence heat evolved = 722·1 grm.-units Cent.

Experiment 192.—Exploded 400 grs. F. G.

	Fahr.
Temperature of calorimeter before explosion . .	53°·95
" " after " . .	69°·59
Hence difference . . . . . $15°·64+1°·28=$	16°·92

Hence heat evolved = 730·7 grm.-units Cent.

Experiment 193.—Fired 5960 grs. = 386·2 grms. mining powder in cylinder No. 6, containing 14,900 grs.

Temperature of gas = 55°·5 Fahr. = 13°·1 Cent. Bar. 30·025 = 762·35 mm.
Amount of gas = 27″·94 − 8″·35 = 19″·59.
= 444·8 × 19·59 + 18 cub. inches.
= 8731·63 cub. inches.
= 143,076·49 c.c. at 13°·1 Cent., and 762·35 mm.
= 143,518·9 c.c. at 13°·1 Cent., and 760 mm.
= 136,944·2 c.c. at 0° Cent., and 760 mm.
= 354·6 times original volume.

Experiment 194.—Fired 4650 grs. (301·3 grms.) mining powder in cylinder containing 15,500 grs.

In letting the gas escape, found for the first time that the gas lighted, giving rise to an intensely suffocating smell of sulphurous acid, showing, as was indeed otherwise apparent, that sulphydric acid was present in large quantities. Sealed up gases for examination.

Did not take out the deposit as usual, but after the gases had escaped, filled the cylinder, by displacement, with distilled water, entirely freed from air by long boiling.

On the water touching the deposit, it decrepitated with considerable sharpness. When the cylinder was full it was entirely sealed, and reopened after an interval of about forty-eight hours. The solution was then decanted into bottles, freed from oxygen, and sealed for examination.

δ.	A.	a.	Crush.	Pressure.
·30	·0833	·0417	·015	5·04 tons per square inch.

Experiment 195.—Fired 5960 grs. = 386·2 grms. Curtis and Harvey's No. 6, in cylinder No. 6.

Temperature of gas = 60°·8 Fahr. = 16°·0 Cent. Bar. 30″·430 = 772·9.
Amount of gas = 444·8 × 13·10 + 18 cub. inches.
= 5,844·88 cub. inches.
= 95,774·2 c.c. at 772·9 and 16°·0 Cent.
= 97,399·8 c.c. at 16°·0 Cent. at 760 mm.
= 92,004·6 c.c. at 0° Cent., and 760 mm.
= 238·23 vols.

Experiment 196.—Fired 4650 grs. = 301·3 grms. Curtis and Harvey's No. 6, in cylinder containing 15,500 grs. Took all the precautions described in Experiment 194; observed gas issuing from vessel would not light.

δ.	A.	a.	Crush.	Pressure.
·30	·0833	·0417	·015	5·04 tons per square inch.

Experiment 197.—Fired 10,000 grs. of mining powder in cylinder containing 15,500 grs. of water. A good deal of gas escaped past crusher-plug.

δ.	A.	a.		Crush.		Pressure.
·700	·0833	·0417	A	·220	=	20·8 tons per square inch.
			B	·221	=	20·8 ,,
			C	·226	=	21·2 ,,

Deposit approximately = 2025 grs. water.

Experiment 198.—Fired 10,000 grs. Curtis and Harvey's No. 6.

The greater proportion of the gases escaped, the gas getting between the steel barrel and the coil, by the screw of the crusher-plug, causing the coil to crush, and indenting the steel and the coil in a very remarkable manner.

δ.	A.	a.		Crush.		Pressure.
·70	·0833	·0417	A	·214	=	19·95 tons per square inch.
			B	·197	=	19·11 „
			C	·197	=	19·11 „

Experiment 199.—A series of experiments in guns of various calibres with mining powder.

Experiment 200.—Fired cylinder hooped with B. R. iron No. 3, and with a capacity of 11,000 grs. water, with a charge of 8750 grs. pebble, and 2250 grs. F. G.—11,000 grs. in all. Copper in crusher-plug crushed beforehand to 35 tons.

Head of crusher-plug broke off by the explosion, and gas escaped, taking, as nearly as could be guessed, from one to two seconds to escape.

Outside diameter of cylinder before firing	.	10″·368
„ „ after „	.	10″·393

Pressure developed over 39 tons, but not reliable, owing to the escape of the gases.

Experiment 201.—Fired cylinder hooped with Siemens' mild steel No. 2, and with a capacity of 11,200 grs. water, with a charge of 11,200 grs. powder, consisting of 8750 grs. pebble and 2450 grs. F. G.

Gas escaped with great rapidity past the firing cone, which was of course destroyed; great difficulty found in extracting the crusher-piston, which had been jammed by the compression of the chamber in which it was placed. Its record was therefore valueless.

Experiment 202.—Fired same cylinder with a charge of 13,640 grs. powder, of which 8375 grs. were pebble, the rest F. G. Crusher-plug blew out before charge fully fired.

Experiment 225.—Fired 9000 grs. pebble and 3000 grs. F. G. in cylinder No. 2, containing 12,680 grs. water, less 670 grs. occupied by internal crusher-gauge. One internal crusher used; gas escaped slowly.

δ.	A.	a.		Crush.		Pressure.
1·0	·0417	·0833	B crusher	·193	=	42·52 tons per sq. inch.
			C „	·193	=	42·72 „

Experiment 230.—Fired in No. 2 cylinder (Siemens'), containing 12,680 grs., 11,360 grs. mining powder, same as that tested in the 2·5-inch B.L. gun on 4th September 1878. The gas escaped through the insulated cone, almost at once. It did not escape with any violence.

Pressures indicated were as follow:—

δ.	A.	a.		Crush.		Pressure.
1	·0417	·0833	A	·165	=	36·8 tons per square inch.
				(A, doubtful; piston being jammed.)		
			B	·200	=	43·9 tons per square inch.
			C	·200	=	43·9 ,,

Experiment 233.—Fired 9000 grs. pebble, and 4000 grs. F. G., total 13,000 grs. (842·4 grms.), in No. 2 Siemens' cylinder, cubic contents, 12,680 grs.—2000 grs. for two internal crusher-gauges; total contents, 10,680 grs. The pressure forced out the closing-plugs by shearing the threads.

δ.	A.	a.		Crush.		Pressure.
1·21	·0417	·0833	A crusher	·256	=	55·6 tons per sq. inch.
			B ,,	·256	=	55·6 ,,
			C ,,	·260	=	56·8 ,,

Note.—(*Added 9th March*, 1880.)

Since this memoir was submitted to the Society, we have been led, in consequence of a communication made to us by Dr Debus, to modify considerably our views with regard to the formation of hyposulphite.

The experiments rendered necessary by Dr Debus's discovery are fully described and discussed in a note submitted to the Royal Society,* but as the facts there given have led us to the conclusion "that although it would seem that in certain cases and under certain exceptional circumstances potassium hyposulphite does exist as a secondary, it exists in no case as a primary product, and should not, therefore, be reckoned among the normal constituents of powder-residues," we have recalculated the whole of our analytical results, and we append two tables, Nos. 12 and 13, giving for each experiment the products of decomposition calculated on the hypothesis that prior to removal from the explosion-vessel the whole of the hyposulphite found was in the form of mono- or polysulphides.

* *Proc. Roy. Soc.*, vol. xxx., p. 198.

TABLE 12.—*Showing the mean analytical results obtained from an examination of powders; showing also the same particulars*

No. of experiments.	Nature of powder.	Mean density of products of combustion.	Percentage composition by: Carbonic anhydride.	Carbonic oxide.	Nitrogen.	Sulphhydric acid.
8	Pebble, W. A.	·10	46·66	14·76	32·75	3·13
7		·20	44·78	16·09	31·31	4·23
9		·30	47·03	15·51	31·71	2·90
12		·40	49·52	13·95	32·16	1·70
14		·50	49·82	13·36	32·19	1·96
37		·60	49·48	13·75	31·83	2·24
38		·70	49·93	12·51	32·08	3·18
43		·80	51·54	11·88	32·61	1·96
77		·90	51·75	10·87	32·72	2·13
		Means	48·95	13·63	32·15	2·60
		Highest	51·75	16·09	32·75	4·23
		Lowest	44·78	10·87	31·31	1·70
1	R. L. G., W. A..	·10	49·00	8·98	35·60	4·06
3		·20	46·56	11·47	35·13	3·58
4		·30	49·35	11·60	32·96	3·11
11		·40	50·25	10·84	34·23	1·93
70		·50	47·21	17·04	30·29	1·61
39		·60	46·29	14·52	32·40	4·29
96		·60	50·22	13·93	31·74	1·62
41		·70	49·75	13·38	31·94	2·85
44		·80	51·62	12·16	32·16	1·56
68		·90	52·65	10·73	32·65	1·90
		Means	49·29	12·47	32·91	2·65
		Highest	52·65	17·04	35·60	4·29
		Lowest	46·29	8·98	30·29	1·56
16	F. G., W. A.	·10	44·76	16·25	32·57	2·26
17		·20	47·41	12·35	32·35	3·76
18		·30	50·45	11·33	32·22	2·21
19		·40	51·79	10·31	32·54	2·00
75		·50	51·04	10·38	33·15	2·20
40		·60	52·00	9·60	33·28	2·26
42		·70	53·02	7·91	34·26	2·03
47		·80	51·80	8·32	34·64	2·61
69		·90	53·34	7·71	33·81	2·95
		Means	50·63	10·47	33·21	2·48
		Highest	53·34	16·25	34·64	3·76
		Lowest	44·76	7·71	32·22	2·00
78	R. F. G., W. A.	·70	52·40	8·86	34·51	1·60
79	Spanish spherical . . .	·70	53·34	4·62	37·80	2·74
196	Curtis and Harvey, No. 6 . .	·30	50·22	7·52	34·46	2·08
194	Mining powder	·30	32·15	33·75	19·03	7·10

the solid and gaseous products of decomposition of Pebble, R. L. G., and F. G. with respect to four other powders.

volume of the gas.			Percentage composition by weight of the solid residue.								
Marsh-gas.	Hydrogen.	Oxygen.	Potassium carbonate.	Potassium sulphate.	Potassium monosulphite.	Potassium sulphocyanate.	Potassium nitrate.	Potassium oxide.	Ammonium sesquicarbonate.	Sulphur.	Charcoal.
...	2·70	...	58·56	15·84	20·50	0·09	0·51	...	0·17	4·33	...
...	3·59	...	58·01	13·85	20·41	0·06	...	...	0·09	7·58	...
...	2·84	...	60·09	12·74	19·24	0·21	0·03	...	0·17	7·52	...
0·32	2·35	...	57·25	13·69	18·52	0·25	0·08	...	0·07	8·74	1·40
0·58	2·08	...	57·04	12·12	23·02	0·23	0·20	...	0·08	7·31	...
0·55	2·15	...	59·00	13·82	17·68	0·36	0·32	...	0·06	8·76	...
0·35	1·95	...	54·64	13·91	22·72	0·41	0·26	...	0·06	8·00	...
0·34	1·67	...	62·35	10·94	16·84	0·06	0·33	...	0·08	9·40	...
0·68	1·85	...	66·43	9·45	11·92	0·59	0·44	...	0·12	11·05	...
0·31	2·35	...	59·26	12·93	18·98	0·25	0·24	...	0·10	8·08	0·16
0·68	3·59	...	66·43	15·84	23·02	0·59	0·51	...	0·17	11·05	1·40
...	1·67	...	54·64	9·45	11·92	0·06	0·03	...	0·06	4·33	...
0·29	2·07	...	55·41	21·58	16·68	...	0·59	...	0·06	4·93	0·75
0·07	2·62	0·57	55·47	24·44	13·08	0·05	0·12	...	0·06	6·76	0·02
...	2·98	...	54·16	25·03	13·76	0·05	0·03	...	0·04	6·93	...
0·28	2·47	...	51·82	24·35	17·00	0·17	0·13	...	0·04	6·49	...
0·84	3·01	...	64·77	4·96	19·47	0·30	0·53	...	0·11	9·86	...
0·36	2·14	...	66·43	10·90	11·85	0·28	0·46	...	0·09	9·99	...
0·35	2·14	...	64·88	11·16	13·91	0·26	...	...	0·11	9·68	...
0·55	1·53	...	63·25	11·04	15·34	0·51	0·44	...	0·08	9·34	...
0·77	1·72	...	67·00	8·88	10·92	0·25	0·18	...	0·11	12·66	...
0·80	1·27	...	67·16	8·71	12·50	0·38	0·20	...	0·15	10·90	...
0·43	2·19	0·06	61·03	15·10	14·45	0·22	0·27	...	0·08	8·74	0·08
0·84	3·01	0·57	67·16	25·03	19·47	0·51	0·59	...	0·15	12·66	0·75
0·07	1·27	...	51·82	4·96	10·92	0·05	0·03	...	0·04	4·93	...
0·18	3·83	0·15	52·43	19·00	18·30	...	0·21	5·74	0·07	4·25	...
...	4·13	...	60·20	24·55	8·30	0·02	0·08	...	0·15	6·70	...
...	3·51	0·28	47·17	23·24	19·23	0·07	0·10	...	0·01	10·18	...
...	3·36	...	48·37	23·46	21·50	0·08	0·10	...	0·04	6·45	...
0·27	2·96	...	57·97	21·45	12·55	0·07	0·09	...	0·08	7·79	...
0·18	2·68	...	45·55	24·15	20·12	0·17	0·18	3·49	0·01	6·33	...
0·50	2·13	0·15	48·39	23·61	20·90	0·26	0·21	...	0·03	6·60	...
0·41	2·04	0·18	47·80	23·15	21·98	0·26	0·28	...	0·04	6·49	...
0·16	2·04	...	54·17	19·64	18·88	0·27	0·28	...	0·03	6·73	...
0·19	2·96	0·08	51·34	22·47	17·97	0·13	0·17	1·02	0·05	6·83	...
0·50	4·13	0·28	60·20	24·55	21·98	0·27	0·28	5·74	0·15	10·18	...
...	2·04	...	45·55	19·00	8·30	...	0·08	...	0·01	4·25	...
0·12	2·51	...	60·17	22·35	9·14	0·04	0·06	...	0·05	8·19	...
...	1·29	0·21	35·66	48·55	7·72	0·04	0·95	...	0·04	7·04	...
2·46	3·26	...	59·10	21·65	12·42	...	0·29	...	0·09	6·45	...
2·73	5·24	...	41·36	0·59	37·10	2·95	0·09	...	1·78	14·11	2·02

TABLE 13.—*Composition by weight of the products of combustion of 1 gravimetric*

No. of experiments.	Nature of powder.	Mean density of products of combustion.	Proportions by weight of gaseous products. Carbonic anhydride.	Carbonic oxide.	Nitrogen.	Sulphhydric acid.	Marsh-gas.	Hydrogen.	Oxygen.
8	Pebble, W. A. .	·10	·2634	·0530	·1176	·0137	...	·0007	...
7		·20	·2505	·0572	·1114	·0183	...	·0009	...
9		·30	·2609	·0548	·1120	·0124	...	·0007	...
12		·40	·2683	·0481	·1109	·0071	·0007	·0006	...
14		·50	·2768	·0472	·1137	·0084	·0012	·0005	...
37		·60	·2695	·0477	·1103	·0094	·0011	·0005	...
38		·70	·2748	·0438	·1124	·0135	·0007	·0005	...
43		·80	·2785	·0409	·1121	·0082	·0007	·0004	...
77		·90	·2743	·0367	·1103	·0087	·0014	·0005	...
		Means	·2685	·0477	·1123	·0111	·0006	·0006	...
		Highest	·2785	·0572	·1176	·0183	·0014	·0009	...
		Lowest	·2505	·0367	·1103	·0071	...	·0004	...
1	R. L. G., W. A. .	·10	·2653	·0309	·1226	·0170	·0006	·0005	...
3		·20	·2497	·0391	·1198	·0148	·0001	·0006	·0022
4		·30	·2633	·0394	·1119	·0128	...	·0007	...
11		·40	·2702	·0371	·1172	·0080	·0006	·0006	...
70		·50	·2601	·0581	·1053	·0068	·0017	·0007	...
39		·60	·2480	·0495	·1101	·0177	·0007	·0005	...
96		·60	·2672	·0471	·1074	·0067	·0007	·0005	...
41		·70	·2655	·0454	·1085	·0118	·0011	·0004	...
44		·80	·2651	·0397	·1051	·0062	·0014	·0040	...
68		·90	·2760	·0358	·1089	·0077	·0015	·0003	...
		Means	·2630	·0422	·1117	·0109	·0008	·0009	·0002
		Highest	·2760	·0581	·1226	·0177	·0017	·0040	·0022
		Lowest	·2480	·0309	·1051	·0062	·0001	·0003	...
16	F. G., W. A. .	·10	·2512	·0580	·1163	·0098	·0004	·0010	·0006
17		·20	·2490	·0413	·1081	·0153	...	·0010	...
18		·30	·2621	·0374	·1065	·0089	...	·0008	·0010
19		·40	·2765	·0350	·1105	·0082	...	·0008	...
75		·50	·2665	·0344	·1102	·0089	·0005	·0007	...
40		·60	·2782	·0327	·1133	·0093	·0003	·0007	...
42		·70	·2804	·0266	·1152	·0083	·0010	·0005	·0006
47		·80	·2752	·0281	·1171	·0107	·0008	·0005	·0007
69		·90	·2812	·0259	·1134	·0120	·0003	·0005	...
		Means	·2689	·0355	·1123	·0101	·0004	·0007	·0003
		Highest	·2892	·0580	·1171	·0153	·0010	·0010	·0010
		Lowest	·2490	·0259	·1065	·0082	...	·0005	...
78	R. F. G., W. A. .	·70	·2686	·0289	·1126	·0064	·0002	·0006	...
79	Spanish spherical .	·70	·2457	·0136	·1108	·0097	...	·0003	·0007
196	Curtis&Harvey,No.6	·30	·2593	·0247	·1132	·0083	·0046	·0008	...
194	Mining powder .	·30	·2279	·1522	·0858	·0389	·0070	·0017	...

gramme of fired gunpowder of the undermentioned natures, and of various densities.

Proportions by weight of the solid residue.									Proportion by weight of total gaseous products.	Proportion by weight of total solid products.	Water.
Potassium carbonate.	Potassium sulphate.	Potassium monosulphide.	Potassium sulphocyanate.	Potassium nitrate.	Potassium oxide.	Ammonium sesquicarbonate.	Sulphur.	Charcoal.			
·3174	·0858	·1111	·0005	·0027	...	·0009	·0234	...	·4484	·5418	·0095
·3203	·0765	·1127	·0003	...	...	·0005	·0419	...	·4383	·5522	·0095
·3303	·0700	·1058	·0012	·0002	...	·0009	·0413	...	·4408	·5497	·0095
·3176	·0760	·1028	·0014	·0004	...	·0004	·0485	·0077	·4357	·5548	·0095
·3096	·0658	·1249	·0012	·0011	...	·0004	·0397	...	·4478	·5427	·0095
·3257	·0763	·0976	·0020	·0018	...	·0003	·0484	...	·4385	·5520	·0095
·2977	·0758	·1238	·0022	·0014	...	·0003	·0436	...	·4457	·5448	·0095
·3428	·0601	·0926	·0003	·0018	...	·0004	·0517	...	·4408	·5497	·0095
·3711	·0528	·0666	·0033	·0025	...	·0007	·0617	...	·4318	·5587	·0095
·3258	·0710	·1042	·0014	·0013	...	·0005	·0445	·0008	·4409	·5496	·0095
·3711	·0858	·1249	·0033	·0027	...	·0009	·0617	...	·4484	·5587	·0095
·2977	·0528	·0666	·0003	...	...	·0003	·0234	...	·4318	·5418	·0095
·3059	·1191	·0921	...	·0033	...	·0003	·0272	·0041	·4369	·5520	·0111
·3121	·1375	·0736	·0003	·0007	...	·0003	·0380	·0001	·4263	·5626	·0111
·3037	·1403	·0772	·0003	·0002	...	·0002	·0389	...	·4281	·5608	·0111
·2877	·1352	·0944	·0010	·0007	...	·0002	·0360	...	·4337	·5552	·0111
·3601	·0276	·1083	·0017	·0030	...	·0006	·0548	...	·4327	·5561	·0112
·3739	·0614	·0667	·0016	·0026	...	·0005	·0562	...	·4265	·5629	·0111
·3629	·0624	·0778	·0015	...	...	·0006	·0541	...	·4296	·5593	·0111
·3519	·0614	·0853	·0028	·0024	...	·0004	·0520	...	·4327	·5562	·0111
·3802	·0504	·0620	·0014	·0010	...	·0006	·0718	...	·4215	·5674	·0111
·3764	·0488	·0700	·0021	·0011	...	·0008	·0611	...	·4302	·5603	·0111
·3415	·0844	·0807	·0013	·0015	...	·0004	·0490	·0004	·4298	·5591	·0111
·3802	·1403	·1083	·0021	·0033	...	·0008	·0718	·0041	·4369	·5674	·0112
·2877	·0276	·0620	...	...	...	·0002	·0272	...	·4215	·5520	·0111
·2872	·1042	·1003	...	·0011	·0315	·0004	·0233	...	·4372	·5480	·0148
·3434	·1401	·0473	·0001	·0005	...	·0009	·0382	...	·4147	·5705	·0148
·2683	·1321	·1093	·0003	·0005	...	·0001	·0579	...	·4167	·5685	·0148
·2680	·1300	·1192	·0004	·0006	...	·0002	·0358	...	·4310	·5542	·0148
·3269	·1210	·0708	·0004	·0005	...	·0005	·0439	...	·4212	·5640	·0148
·2508	·1330	·1108	·0009	·0010	·0192	·0001	·0349	...	·4345	·5507	·0148
·2674	·1305	·1155	·0014	·0012	...	·0002	·0364	...	·4326	·5526	·0148
·2640	·1278	·1214	·0014	·0015	...	·0002	·0358	...	·4331	·5521	·0148
·2989	·1084	·1042	·0015	·0016	...	·0002	·0371	...	·4333	·5519	·0148
·2861	·1252	·0999	·0007	·0009	·0056	·0003	·0381	...	·4282	·5569	·0148
·3434	·1401	·1214	·0015	·0016	·0315	·0009	·0579	...	·4372	·5705	·0148
·2508	·1042	·0473	...	·0005	...	·0001	·0233	...	·4147	·5480	·0148
·3458	·1285	·0525	·0002	·0003	...	·0003	·0471	...	·4173	·5747	·0080
·2186	·2975	·0473	·0002	·0058	...	·0002	·0431	...	·3808	·6127	·0065
·3413	·1250	·0717	...	·0017	...	·0005	·0372	...	·4109	·5774	·0117
·1945	·0028	·1745	·0139	·0004	...	·0084	·0664	·0095	·5135	·4704	·0161

Note on the Existence of Potassium Hyposulphite in the Solid Residue of Fired Gunpowder.

In our second memoir on fired gunpowder we have discussed in detail that part of M. Berthelot's friendly criticism of our first memoir, which relates to the potassium hyposulphite found by us, in variable proportions, in our analyses of the solid products obtained by the explosion of gunpowder in the manner described. While pointing out that we had taken every precaution in our power to guard against the production of hyposulphite by atmospheric action upon the potassium sulphide during the removal of the hard masses of solid products from the explosion-vessel, and had effectually excluded air from them, when once they were removed until they were submitted to analysis, we admitted the impossibility of guarding against the accidental formation of some hyposulphite during the process of removal, especially in some instances in which the structure of the residue had certainly been favourable to atmospheric action, and in which a more or less considerable development of heat had afforded indications of the occurrence of oxidation.

We contended, however, that the method of analysis, and the precautions adopted by us in carrying it out, precluded the possibility of accidental formation of hyposulphite at this stage of our investigations. With respect to the precautions, we could, and still do, speak with perfect confidence; and we certainly have believed ourselves fully justified in being equally confident with respect to the process adopted by us for the determination of the proportions of sulphide and hyposulphite, inasmuch as we accepted and used in its integrity the method published in 1857 by Bunsen and Schischkoff in their classical memoir on the products of explosion of gunpowder, and adopted since that time by several other investigators who have made the explosion of gunpowder the subject of study, and whose results are referred to in our first memoir.

Imposing implicit confidence in the trustworthiness of this method of analysis, emanating as it did from one of the highest authorities in experimental research, we considered ourselves fully justified in maintaining that the very considerable variations in the amount of hyposulphite found in different analyses, carried out as nearly as possible under like conditions, and the high proportions of sulphide obtained in several of those analyses, afforded substantial proof that accidental oxidation during the collection and analysis of the residues was not sufficient to account for all but the very small

quantities of hyposulphite, which, in M. Berthelot's view, could have pre-existed in the powder-residues. Other facts, established by the exhaustive series of experiments detailed in our first memoir, were referred to by us in our second memoir, in support of the above conclusion (from which we have still no reason whatever to depart). At the same time we described a series of supplementary experiments which had been instituted by us, with a view to obtain, if possible, further decisive evidence as to the probable proportions of hyposulphite and sulphide actually existing in the residues furnished by the explosion of gunpowder in closed vessels.

In the first place, the residues obtained by the explosion of charges of R. L. G. and pebble powders were submitted to special treatment. Portions of each, consisting exclusively of large masses, were very speedily detached and removed from the explosion-vessels, and sealed up in bottles freed from oxygen, having been exposed to the air only for a few seconds. Other portions of the same residues were very finely ground, and exposed to the air for 48 hours. As was stated in our recent memoir, the portions of the residues treated in the last-named manner contained very large proportions of hyposulphite (although in one of them there still remained about 3 per cent. of sulphide), while those portions which had been for only a brief period exposed to air (and which presented but small surfaces) were found to contain from 5 to 8·5 per cent. of hyposulphite. As, throughout our entire series of previous experiments, no accidental circumstances had occurred which even distantly approached the special conditions favourable to the oxidation of the sulphide presented in these particular experiments, we considered ourselves fully justified in concluding that the non-discovery of any sulphides in the analyses of residues furnished by the fine-grain powder in three out of the whole series of experiments, was not due to accident in the manipulations; and that in those instances, in our several series of experiments, in which large quantities of hyposulphite were found, the greater proportion of that substance must have existed before the removal of the residues from the explosion-vessel.

Not suffering the question to rest there, however, we proceeded, in the second place, to adopt new precautions, in two special experiments, for guarding against the possible formation of hyposulphite in the removal of the residues from the explosion-vessel, and their preparation for analysis.

Distilled water, carefully freed from air by long-continued boiling, was syphoned into the vessel when it had cooled after the

explosion, and thus no air was ever allowed to come into contact with the solid products. When the vessel was quite filled with water it was closed, and, after having been left at rest for a sufficient time to allow the residue to dissolve completely, the solution was rapidly transferred to bottles which had been freed from oxygen. These, when completely filled with the liquid, were hermetically sealed until the contents were submitted to analysis in accordance with the usual method, when they furnished respectively 4 and 6 per cent. of hyposulphite. These results corresponded closely to others obtained by the analysis of seven residues obtained in experiments with P., R. L. G., and L. G. powders, in which there were no peculiarities assignable as a possible reason why the proportions of hyposulphite should be so much lower in these cases than in other experiments carried out with the same powders under as nearly as possible the same conditions.

By the results obtained under the various conditions pointed out in the foregoing, we are forced to the conclusion that the discovery of a small or a larger proportion of hyposulphite by the analysis of the powder-residue, obtained as described, is consequent upon some slight variation (apparently not within the operator's control) attending the explosion itself; but that hyposulphite does exist, though generally not to anything like the extent we were at first led to believe, as a normal and not unimportant product of the explosion of powder in a closed space.

Some time after the submission of our second memoir to the Royal Society, we received a communication from Professor Debus, which has led us to institute a further series of experiments bearing upon this question of the existence of hyposulphite, and the results we have arrived at have led us so greatly to modify our views on this point, that it is our duty to communicate them without loss of time to the Royal Society.

As introductory to these, it is necessary to repeat the account, given in our first memoir, of the method pursued by us for determining the proportions of potassium monosulphide and hyposulphite in a powder-residue.

The solution of the residue, prepared by the several methods already described, was separated by filtration, as rapidly as possible, from the insoluble portion, the liquid being collected in a flask, in which it was at once brought into contact with pure ignited copper oxide. The solution and oxide were agitated together, from time to time, in the closed flask, the two being allowed to remain together

until the liquid was perfectly colourless. In a few instances the oxide was added in small quantities at a time, in others the sufficient excess was added at once, with no difference in the result obtained. The only points in which this method differed from that described by Bunsen and Schischkoff in their memoir, was in the employment of a flask well closed with an indiarubber bung for the stoppered cylinder which was employed by them; and in occasionally curtailing somewhat the prescribed period (two days) for which the liquid and the copper oxide were allowed to remain together, the operation being considered complete when the solution had become colourless. Bunsen and Schischkoff prescribed that the liquid when separated by filtration from the mixed copper oxide and sulphide obtained in the foregoing treatment, is to be divided into seven equal volumes, in one of which the amount of hyposulphite may be most simply estimated by acidifying it with acetic acid, and then titrating with a standard iodine solution. This course was adopted by us, and it will therefore be seen that we departed in no essential point whatever from the method of Bunsen and Schischkoff, which we had considered ourselves fully warranted in adopting, without questioning its trustworthiness.

We were informed, however, last July by Dr Debus, that in submitting potassium polysulphides to treatment with copper oxide, he had found much hyposulphite to be produced, even when air was perfectly excluded, it having been in the first instance ascertained that the several polysulphides experimented with did not contain any trace of hyposulphite. We proceeded at once to confirm the correctness of his observations by submitting potassium polysulphides to treatment with copper oxide, proceeding exactly according to the method prescribed by Bunsen and Schischkoff for the treatment of powder-residues. In one experiment we obtained as much as 87·1 per cent. of potassium hyposulphite (calculated upon 100 parts of potassium monosulphide). Even in an experiment with pure potassium monosulphide, we obtained 11·6 per cent. of hyposulphite upon its treatment for the usual period with copper oxide.

We next proceeded to convince ourselves that by substituting zinc chloride solution for copper oxide, the sulphur existing in solutions of potassium mono- and polysulphides might be abstracted, according to the usual method of operation, without producing more than the very small quantities of hyposulphite ascribable to the access of a little air to the sulphides before or during the method of treatment.

Having confirmed the validity of Dr Debus's objection to Bunsen and Schischkoff's method, and established the trustworthiness of a

modification of that method (zinc chloride being substituted for copper oxide), we proceeded to submit to precisely similar treatment with these two reagents portions of solutions obtained by dissolving, with total exclusion of air (in the manner described in our last memoir and the present note), the residue furnished by special experiments with P., R. L. G., and F. G. powders, exploded under the usual conditions obtaining in our researches, and in quantities ranging from 4200 to 35,000 grs. (272·2 grms. and 2268 grms.). The following is a tabulated statement of the results obtained by the two modes of treatment, and of the differences between the proportions of hyposulphite obtained by treatment of portions of one and the same residue with the two different reagents under conditions as nearly alike as possible:—

TABLE 1.

No. of experiment.	Description of powder.	Quantity used.		Density of charge.	Amount of hyposulphite furnished by 100 parts of powder with employment of—		
		Grains.	Grams.		Zinc chloride.	Copper oxide.	Difference.
245	P.	3,396	220·05	0·3	·12	1·93	1·81
241	P.	5,660	366·76	0·5	·07	2·46	2·39
246	R. L .G.	4,200	272·16	0·4	·05	1·43	1·38
244	R. L. G.	5,250	340·19	0·5	·06	1·58	1·52
243	F. G.	4,523	293·41	0·4	·07	1·56	1·49
242	F. G.	6,300	408·23	0·6	·27	2·26	1·99
247	P.	35,000 (5 lb.)	2,267·97	0·23	·78	2·82	2·04

For purposes of comparison, we subjoin a statement of the lowest proportions of hyposulphite furnished by 100 parts of the three powders used in our general series, and also the proportions, similarly expressed, which were obtained in the experiments with sporting and mining powder, the residues of which were dissolved with the same special precautions adopted in the case of the experiments given in Table 1.

TABLE 2.

No. of experiment.	Nature of powder.	Amount of hyposulphite in 100 parts of gunpowder used.	Remarks.
7	Pebble	2·06	Lowest proportions furnished by the respective powders.
44	R. L. G.	1·75	
17	F. G.	3·04	
196	Curtis and Harvey No. 6	2·28	Special precautions taken in collecting the residue.
194	Mining powder	2·77	

In reference to the foregoing numerical statements, we have to offer the following observations:—

1. Substituting zinc chloride for copper oxide as the precipitant of the sulphur which existed in the form of sulphide in solutions of powder-residues to which air had not had access at all until the time of its treatment with the zinc chloride, the amount of hyposulphite existing in solution after such treatment was found to range from 0·05 to 0·78 in 100 parts of gunpowder, while the treatment of portions of the same solutions with copper oxide, in the precise manner adopted in our series of experiments, yielded proportions ranging from 1·43 to 2·82 per 100 of powder used. Comparing the results furnished by the two modes of treatment, it will be seen that in the case of the parallel experiment (Experiment 246), which exhibited the least considerable difference in the amount of hyposulphite found, that existing after the copper oxide treatment was about twenty-eight times greater, while in the case of the highest difference (Experiment 241) it was about thirty-four times greater than that found after the treatment with the zinc chloride.

2. It would appear from these results that, in four or five out of seven experiments, no hyposulphite, or at any rate only minute quantities, existed in the residues previous to their solution, and although it would seem to have existed in very appreciable amount in two out of seven residues, the highest proportion found after the zinc chloride treatment was less than one-half the lowest proportion found in our complete series of analyses in which the copper oxide treatment was adopted.

3. A comparison of the results among each other leads, therefore, to the conclusion that potassium hyposulphite cannot be regarded as a normal constituent of powder-residue (obtained in experiments such as those carried out by us), and that M. Berthelot is correct in regarding this salt as an accidental product, which, if existing occasionally in appreciable amount in the solid matter previous to its removal from the explosion-vessel, is formed under exceptional conditions, and then only in comparatively small proportions.

While submitting this as the conclusion to be drawn from our most recent experiments, we are of opinion that the following points deserve consideration in connection with the question whether hyposulphite may not, after all, occasionally exist, as the result of a secondary reaction, in comparatively large proportion in the explosion-vessel before the residue is removed.

It will be observed that although the copper oxide treatment,

when applied to the sulphide in the pure condition (*i.e.*, undiluted with the other potassium compounds found in powder-residue), gave rise to the production of very large proportions of hyposulphite, when polysulphides were used, the highest proportion of that substance found, after the treatment of the particular residues used in the experiments given in Table 1, only amounts to 2·82 per cent. upon the gunpowder (pebble-powder) employed, which corresponds to about 14·5 per cent. of the average proportion of monosulphide existing in the residue furnished by that powder. In observing this, it must be borne in mind that the sulphide existing in powder-residue is always present, in part, and sometimes to a considerable extent, in the form of polysulphide, also, that the experiments with the sulphides were conducted precisely according to the method pursued in the treatment of the powder-residues. It would appear, therefore, as though the mixture of the sulphide with a very large proportion of other salts in solution rendered it less prone to oxidation by the copper oxide than when the undiluted sulphide is submitted to its action.

In comparing with the results furnished by the zinc chloride those obtained by the copper oxide treatment, in the special experiments given above, it is observed that, omitting one exceptional result (Experiment 241), for which we do not attempt to account, the highest proportions of hyposulphite are furnished by those residues which also gave the highest with the zinc chloride, the differences between the results furnished by the two treatments being likewise the highest in these three cases; so also the lowest proportions furnished by the copper oxide treatment correspond to the lowest obtained with the zinc oxide, and the differences between the results furnished by the two methods are in the same manner the lowest in these. It would almost appear, therefore, as though the existence of a very appreciable proportion of hyposulphite in the solution of the residue had some effect in promoting the production of hyposulphite when the residue is submitted to treatment with copper oxide.

In a recalculation of the results of our analyses of the powder-residues upon the assumption that the whole of the hyposulphite obtained existed originally as monosulphide, it is found that, in several instances in which the proportion of hyposulphite was high, the analytical results are much less in accordance with each other than when it is assumed that the hyposulphite found, or at any rate a very large proportion of it, existed as such in the residue before removal from the explosion-vessel. Thus, taking the F. G.

series, in which the MEAN QUANTITY of hyposulphite actually found is about double of that obtained either from the pebble or R. L. G. powders, selecting from this series the three experiments which gave the highest proportions of hyposulphite, and calculating in the manner described in our first memoir the total quantities both of solid and gaseous products; first, from the basis of the analysis of the solid products; secondly, from the basis of the analysis of the gaseous products; and, further, on the assumption that the hyposulphite found existed as hyposulphite either as a primary or secondary product prior to removal from the explosion-vessel, we have as follows:—

Experiment No. 40, F. G. powder.—Density, ·6; hyposulphite found, 18·24 per cent.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solid products .	170·268	125·220*
From analysis of gaseous products .	172·509*	122·979

Experiment No. 42, F. G. powder.—Density, ·7; hyposulphite found, 18·36 per cent.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solid products .	200·191	144·547*
From analysis of gaseous products .	200·220*	144·520

Experiment No. 47, F. G. powder.—Density, ·8; hyposulphite found, 19·95 per cent.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solid products .	231·652	162·335*
From analysis of gaseous products .	229·392*	164·595

* Water included.

Calculating now in the same manner the quantities of solid and gaseous products on the assumption that the hyposulphite found was, prior to removal from the explosion-vessel, in the form of mono- or polysulphide, we have from the same experiments:—

Experiment No. 40.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solid products .	157·273	133·842
From analysis of gaseous products .	168·136	122·979

Experiment No. 42.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solid products .	185·914	155·722
From analysis of gaseous products .	197·118	144·520

Experiment No. 47.

	Calculated solid products. Grms.	Calculated gaseous products. Grms.
From analysis of solid products .	211·462	176·694
From analysis of gaseous products .	223·561	164·595

Lastly, we still think that the following facts, given in our second memoir, must not be overlooked in considering the question of possible occasional existence of considerable proportions of hyposulphite, viz.:—That "the production of high proportions of hyposulphite was but little affected by any variations in the circumstances attending the several explosives (*i.e.*, whether the space in which the powder was exploded were great or small), excepting that the amount was high in all three cases when the powder was exploded in the largest space; on the other hand, a great reduction in the size of grain of the gunpowder used appeared to have a great influence upon the production of hyposulphite, as when passing from a very large-grain powder (P. or R. L. G.) to a fine-grain powder (F. G.). Thus, the production of hyposulphite exceeded 20 per cent. (on the solid residue) in only three out of nine experiments with P. powder, in three out of ten with R. L. G., and in seven out of nine with F. G.; while it was below 10 per cent. in four out of nine experiments with P. powder, in five out of ten with R. L. G., and in only one out of nine with F. G. powder." The experiments made with these several powders followed in no particular order, and no circumstance existed in connection with them to which these great differences in the results obtained could be ascribed.

We append a recalculation of the mean results of our three series of analysis, adding the values of the hyposulphite found, as monosulphide, to the amount of sulphide actually found, and we hope to be allowed to add to our second memoir a similar recalculation of the whole of our analyses.

This recalculation develops (as we pointed out in our second memoir must necessarily be the case) a more or less considerable

deficiency of oxygen in the total products of explosion; there is, however, in every instance, also a deficiency of hydrogen, and it may, therefore, be reasonably concluded that the deficiencies in the total quantities of the oxygen and the hydrogen in the powder used, which are unaccounted for in the products found, on the assumption that variable proportions of the total hyposulphite found actually existed in the residues as SULPHIDE, are properly accounted for by assuming that the missing quantities of these elements actually existed among the products as water, the amount of which it was obviously impossible to determine.

In conclusion, we have to state that we considered it right, in consequence of the error discovered in the method adopted for the examination for hyposulphite, to repeat the experiments described in our first memoir as having been made by us, with the view of ascertaining whether hyposulphite could exist at temperatures approaching those to which the solid products of explosion were actually subjected in the explosion-vessels in our experiments.

To test this point, we submitted, for between ten minutes and a quarter of an hour, to the highest heat (about 1700° Cent.) of a Siemens' regenerative furnace, two platinum crucibles, one filled with powder-residue, the other with potassium hyposulphite. At the conclusion of the exposure, and while the crucibles were still red hot, they were plunged into water, deprived of air by long-continued boiling, and at once sealed. The powder-residue was found still to contain 1·27 per cent. of hyposulphite, while the crucible with the pure salt consisted of a mixture of sulphate and sulphide, but with an amount of 2·1 per cent. of hyposulphite.

It is probable that, if the exposure had been still longer continued, the hyposulphite would have altogether disappeared, and the experiment can only be taken as proving that the hyposulphite, especially if mixed with other salts, is neither quickly nor readily decomposed, even at very high temperatures.

[TABLE 3.

TABLE 3.—*Showing the mean composition by weight of the products of combustion of 1 grm. of gunpowder of the undermentioned natures, when the whole of the hyposulphite found is supposed originally to have existed in the form of sulphide.*

Nature of powder.	Proportions by weight of gaseous products.							Proportions by weight of solid products.									Proportion by weight of gaseous products.	Proportion by weight of solid products.	Water.
	Carbonic anhydride.	Carbonic oxide.	Nitrogen.	Sulphydric acid.	Marsh-gas.	Hydrogen.	Oxygen.	Potassium carbonate.	Potassium sulphate.	Potassium monosulphide.	Potassium sulphocyanide.	Potassium nitrate.	Potassium oxide.	Ammonium sesquicarbonate.	Sulphur.	Charcoal.			
Pebble	·2685	·0480	·1122	·0111	·0006	·0006	...	·3258	·0710	·1042	·0014	·0013	...	·0005	·0445	·0008	·4409	·5496	·0095
R.L.G.	·2630	·0422	·1117	·0109	·0008	·0009	·0002	·3415	·0844	·0787	·0013	·0015	...	·0004	·0495	·0004	·4298	·5593	·0111
F.G.	·2689	·0355	·1123	·0101	·0004	·0007	·0003	·2861	·1252	·0999	·0007	·0009	·0056	·0003	·0381	...	·4282	·5569	·0148

VII.

HEAT-ACTION OF EXPLOSIVES.

(*Lecture delivered at the Institution of Civil Engineers,* 1884.)

EXAMPLES of explosive substances will readily occur to all of you. The salient peculiarities of some of the best known may roughly be defined to be the instantaneous, or at least the extremely rapid, conversion of a solid or fluid into a gaseous mass occupying a volume many times greater than that of the original body, the phenomenon being generally accompanied by a considerable development of measurable heat, which heat plays a most important part not only in the pressure attained, if the reaction take place in a confined space, but in respect to the energy which the explosive is capable of generating.

Fulminates of silver and mercury, picrate of potassa, guncotton, nitro-glycerine, and gunpowder, may be cited as explosives of this class.

But you must not suppose that substances such as I have just named are the only true explosives. In these solid and liquid explosives, which consist generally of a substance capable of being burnt, and a substance capable of supporting combustion, in, for example, guncotton or gunpowder, the carbon is associated with the oxygen in an extremely condensed form. But the oxidisable and oxidising substances may themselves, prior to the reaction, be in the gaseous form; as, for instance, in the case of mixtures of air or oxygen with carbonic oxide, of marsh-gas with oxygen, or of the mixture of hydrogen and oxygen forming water, which, if regard be had to the weight of the combining substances, forms an explosive possessing a far higher energy than is possessed by any other known substance.

But these bodies do not complete the list, and, under certain circumstances, many substances ordinarily considered harmless must be included under the head of explosives.

Finely-divided substances capable of oxidation, or certain vapours, form, when suspended in, or diluted with, atmospheric air, mixtures which have been unfortunately the cause of many serious explosions.

Minute particles of coal floating in the atmosphere of coal-mines have either originated explosions, or in a very high degree intensified the effects of an explosion of marsh-gas. Flour-dust and sulphur-dust suspended in the air have produced like disastrous results. Lines of demarcation are generally difficult of definition, and the line between explosive and non-explosive substances forms no exception to the rule; but, from the instances I have given, you will note that an explosive may be either solid, liquid, or gaseous, or any combination of these three states of matter.

In the course of my lecture, I propose, in the first instance, to give you a short account of the substances of which some explosives are composed, illustrating my meaning by giving you the composition of one or two which may be considered as types, and which are well known to you.

I shall, in the second place, show the changes which occur when our explosives are fired; and shall endeavour to give you some idea of the substances formed, of the heat developed, of the temperature at which the reaction takes place, and of the pressure realised, if the products of our explosive be absolutely confined in a strong enough vessel, as well as of the experiments which have been made, and the apparatus which has been used either directly to ascertain or to verify the facts required by our theory.

I shall in certain cases suppose our explosives to be placed in the bore of a gun, and shall endeavour to trace their behaviour in the bore, their action on the projectile, and on the gun itself. I shall, at the same time, describe to you the means and apparatus that have been employed to ascertain the pressure acting on the projectile and on the walls of the gun, and to follow the motion of the projectile itself in its passage through the bore.

Let us take, suppose at the temperature 0° Cent., and at the pressure 760 mm. of mercury, two equal volumes of the gases hydrogen and chlorine, which when combined produce hydrochloric acid. I have the gases in this tube, and let us apply a light; you will observe that the mixture explodes violently, with considerable evolution of heat. Now this is perhaps as simple a case of an explosive as we can have.

If we suppose the gases to be exploded in an indefinitely long

cylinder, closed at one end, and with an accurately fitting piston working in it, and if we suppose the gases (fired, you will remember, at 0° Cent. and atmospheric pressure) to be again reduced to the temperature and pressure from which we started, the piston will descend to its original position, and the gases will occupy the same space as before they were exploded.

If we now suppose that we had, in a calorimeter, measured the quantity of heat produced by the explosion, that quantity of heat, about 23,000 grm.-units per gramme of hydrogen, or about 600 grm.-units per gramme of the mixture, expresses, without addition or deduction, the total amount of work stored up in the unexploded mixture, and from that datum, knowing the specific heat, we are able to deduce not only the temperature at which the explosion takes place, but the maximum pressure produced at the moment of explosion, and the work which the gases, in expanding under the influence of the heat evolved, are capable of performing.

If, instead of a single volume each of hydrogen and chlorine, we take two volumes of hydrogen and one of oxygen (which when combined produce water), or by weight two parts of hydrogen and sixteen of oxygen, and explode them as I now do, you will observe that there is a still more violent explosion, and I may add that there is a still greater development of heat.

If, as before, we supposed the explosion carried on in an indefinitely long cylinder, the piston, on the gases being brought back to the temperature and pressure existing before the charge was fired, would no longer stand at its original height, but at two-thirds of that height, the three volumes would be condensed into two, and the heat determined by our calorimeter, about 29,000 grm.-units per gramme of hydrogen, about 3300 grm.-units per gramme of the gaseous water produced by the explosion is increased above what may be considered the true heat of the explosion by the condensation which the aqueous vapour has suffered in passing from three to two volumes.

From the heat determined, however, we are able as before to deduce the temperature of explosion, the pressure exerted on the walls of a close vessel at the instant of maximum temperature, and the energy stored up in the exploded gases.

I have mentioned that the potential energy stored up in this mixture of hydrogen and oxygen is, if taken with reference to its weight, higher than that of any other known mixture, and it may fairly be asked why should such an explosive, whose components

are so readily obtainable, not be more largely employed as a propelling or disruptive agent?

There are several objections; but you will readily appreciate one when I point out that if we assume a kilog. of gunpowder forming a portion of a charge for a gun, to occupy a litre or a decimetre cubed, a kilog. of hydrogen, with the oxygen necessary for its combustion, would at zero and at atmospheric pressure occupy a volume sixteen thousand times as great.

Let us now pass to guncotton, known also as pyroxylin or trinitro-cellulose. This substance, as you probably know, is prepared by submitting ordinary, but carefully purified, cotton to the action of a mixture of concentrated nitric and sulphuric acids at ordinary temperatures, where a proportion of the hydrogen in the cellulose is replaced by an equivalent amount of nitric peroxide.

Nitro-glycerine is in like manner formed by the action of a mixture of nitric and sulphuric acids on glycerine; but we shall for the present confine our attention to guncotton.

The formula representing guncotton is $C_6H_7 3(NO_2)O_5$, and guncotton itself may be employed in several forms in the flocculent or natural state; or it may be made up into strands, yarns, or ropes; or it may be granulated or made into pellets; or it may be highly compressed into slabs or discs, in which last form it is almost invariably used for industrial or military purposes, and for which we are so largely indebted to the labours and researches of my friend and colleague, Sir Frederick Abel.

Samples of all these forms are on the table before you.

When guncotton is fired, practically the whole of its constituents, which before ignition were in the solid, assume the gaseous form, and this change is accompanied by a very great development of heat. I now fire a train of different forms of guncotton, and you will note, in the first place, the small quantity of smoke formed, and this may be taken as an indication of the small amount of solid matter in the products of combustion. You will observe, also, that instead of the explosions which took place when our gaseous mixtures were fired, guncotton appears rather to burn violently than explode. This, however, is due to the ease with which the nascent products escape into the atmosphere, so that no very high pressure is set up.

Were we, by a small charge of fulminate of mercury or other means, to produce a high initial pressure, the harmless ignition that you have seen would be converted into an explosion of the most violent and destructive character.

You will finally note that this transformation differs materially from those which we have hitherto considered. In both of these the elements were, prior to the ignition, in the gaseous state, and the energy liberated by the explosion was expressed directly in the form of heat. In the present instance, a very large but unknown quantity of heat has disappeared in performing the work of placing the products of explosion in the gaseous state.

Let me try to show you how large an amount of heat may be absorbed in the conversion of solid matter into the gaseous state.

You are aware that if a gramme of carbon be burned to carbonic anhydride there are about 8000 grm.-units of heat evolved, whereas if a gramme of carbon be burned to carbonic oxide, there are only evolved about 2400 grm.-units. Now *à priori* we may certainly suppose that the assumption by the carbon of the two atoms of the oxygen should result in equal developments of heat, but you will note, from what I have stated, that in the combination with the second atom of oxygen about two and a third times more heat is developed. Whence, then, comes the difference, and where has the heat disappeared which our calorimeter declines to measure? The missing heat may be assumed to have disappeared in performing the work of placing the solid carbon in the gaseous state.

In the case which we have been considering, the oxygen which supports the combustion of the carbon is already in the gaseous state; but with guncotton all the gases are, prior to combustion, in the solid state. Their approximate weights are exhibited in the following table:—

TABLE 1.—*Showing the composition and metamorphosis of pellet guncotton.*

Composition.		Products of Explosion.	
Carbon	24·89	Carbonic anhydride	0·424
Hydrogen	2·69	,, oxide	0·280
Nitrogen	13·04	Hydrogen	0·011
Oxygen	56·66	Nitrogen	0·145
Ash	0·36	Marsh-gas	0·003
Moisture	2·36	Water	0·116
Formula—$C_6H_73(NO_2)O_5$.		Original moisture	0·021

Carbonic oxide and anhydride, nitrogen, hydrogen, aqueous vapour, and a little marsh-gas, are the products of explosion, and their quantities are such that a kilog. of guncotton, such as that with which Sir F. Abel and I have each made so many experiments, will produce, when the gases are reduced to atmospheric pressure and to a temperature of 0° Cent., about 730 litres. In this volume the water produced by the explosion is not included, being at that temperature and pressure in the liquid form. In estimating either

the pressure exerted on the walls of the close vessel, or the potential energy of the guncotton, we have to add to the work done, that is, to the heat absorbed by the great expansion from the solid state into the number of volumes I have indicated, the potential energy due to the heat at which the reaction takes place.

As might be expected from the definite nature of the chemical constitution of guncotton, the constituents into which it is decomposed by explosion do not very greatly vary; the chief point to be observed being that the higher the tension at which the explosion occurs, the higher is the quantity of carbonic anhydride formed, that is, the more perfect is the combustion.

Gunpowder, the last and most important example I shall select, is also by far the most difficult to experiment with, as well as the most complicated and varied in the decomposition which it undergoes.

To begin with, it is not, like guncotton, nitro-glycerine, and other similar explosives, a definite chemical combination, but is merely an intimate mixture, in proportions which may be varied to a considerable extent, of those well-known substances, saltpetre or nitre, charcoal, and sulphur; and in this country the proportions usually employed are 75 parts of saltpetre, 10 of sulphur, and 15 of charcoal. They do not during manufacture undergo any chemical change, and it is perhaps owing to this circumstance that gunpowder has for so many generations held its place as the first and principal, indeed almost the only, explosive employed for the purposes of artillery and firearms.

One great advantage for the artillerist which gunpowder possesses in being a mixture, not a definite chemical combination, is that when it is fired it does not explode in the strict sense of the word. It cannot, for example, be detonated as can guncotton or nitro-glycerine, but it deflagrates or burns with great rapidity, that rapidity varying largely with the pressure under which the explosion is taking place. As an instance of the difference in the rate of combustion due to pressure, we have found that the time necessary for the combustion of a pebble of powder in free air is about two seconds. The same pebble in the bore of a gun is consumed in about the $\frac{1}{200}$ part of a second; but a more striking illustration of the effect of pressure in increasing or retarding combustion is shown by an experiment devised by Sir F. Abel, and which by his kindness I am able to repeat. It consists in endeavouring to burn powder *in vacuo*, and you will see for yourselves the result of the experiment. The powder refused to explode.

But although the composition of gunpowder is in this country

approximately what I have said, the requirements or experiments of the artillerist have for certain purposes modified in a high degree both the constituents and the physical characteristics of gunpowder.

In the following table are exhibited the composition of the numerous powders with which Sir F. Abel and I have experimented; and the samples which I have upon the table, many of which will be new to some of you, illustrate the irregular forms into which we mould the mixture, which by a misnomer we still call gunpowder. Here you see the forms with which all are familiar, and which are called fine grain and rifled fine grain. Here, a little larger, you see rifled large grain, which at the introduction of rifled guns was the powder then used. Here these small lumps are called pebble-powder, and this powder is that generally used in this country with rifled guns of medium size. Here is a still larger size of service pebble.

TABLE 2.—*Showing the composition of various gunpowders.*

	Powder "A."	Powder "B."	Powder "C."	Powder "D."	Cocoa.	Pebble, W.A.	R.L.G., W.A.	F.G., W.A.	Spanish.	C. & H. No. 6.	Mining.
Saltpetre	·8130	·7783	·6374	·7724	·7883	·7476	·7456	·7391	·7559	·7468	·6192
Sulphur	·0018	·0028	·1469	·0615	·0204	·1007	·1009	·1002	·1242	·1037	·1506
Charcoal	·1671	·1972	·2018	·1543	·1780	·1422	·1429	·1459	·1134	·1378	·2141
Water	·0181	·0217	·0139	·0118	·0133	·0095	·0106	·0148	·0065	·0117	·0161

This form, prismatic, differing from the others both from its regular shape, and from the hole or holes traversing the prisms, is perhaps the most convenient form in which powder can be made up in large charges, while these blocks exhibit still larger masses, representing powders which have been used with success in very large guns. The object of the holes in the prismatic and other powders, is to obtain more uniform production of pressure to ensure the more complete combustion of powder by increasing the burning surface, as the prism is consumed, and consequently diminishes in size.

I draw your particular attention to these samples, because I shall have, before I conclude, something to say about them. You will observe that they are in the prismatic form, and that they differ from the other prisms, with which you can compare them, in being brown in colour instead of black.

Let us now apply a light to trains of different natures, and to some other samples of powder—experiments which I daresay at one

time or another you have made for yourselves—and observe the result. You will note, in the first place, that an appreciable time is taken by the flame to pass from one end to the other; but you will also note an essential difference between this combustion and that I showed you a short time ago with guncotton, viz., that there is a large quantity of what is commonly called smoke slowly diffusing itself in the air.

Now this so-called smoke is really only finely-divided solid matter existing as a fluid, or volatilised only to a very slight extent at the moment and temperature of explosion, and if, adopting means which I shall presently describe to you, we had exploded in a close vessel the powder which we have just burned in the air, and allowed the vessel to stand for a few minutes, the products would be divided into two classes—one, a dense solid, generally very hard, and always a disagreeably smelling substance; the other, colourless gases, the odour of which is, I must confess, not much more fragrant than that of the solid matter to which I have referred.

These large bottles on the table contain a portion of the so-called smoke of a charge of 15 lbs. of powder, collected in the manner I have described, in a closed vessel. You will see it is a very solid substance indeed; but as these products are sometimes very protean in their characteristics, I have upon the table one or two other specimens of these residues differing considerably in appearance.

I have also in this steel vessel the products of combustion of 2 lbs. of powder. I shall not now let the gases escape; but after the lecture shall be glad to do so for the benefit of those who have no objection to a disagreeable smell.

If the gases produced by the combustion be analysed, they will be found to consist of carbonic anhydride, carbonic oxide, and nitrogen, as principal constituents, with smaller quantities of sulphhydric acid, marsh-gas, and hydrogen, with—this point depending much on the constitution of the charcoal—always small quantities, and occasionally considerable, of aqueous vapour.

The solid substances are found to consist of, as principal ingredients, variable quantities of potassium carbonate, sulphate, and sulphides, with smaller quantities of sulphocyanate, and ammonium sesquicarbonate.

The annexed table shows by weight the products of combustion in the different powders examined by Sir F. Abel and myself, and I call your special attention to the considerable variations in the decomposition of powders which are intended practically to have the same chemical constitution.

TABLE 3.—*Showing the decomposition of the powders in Table 2.*

Nature of Powder.	Weight, Gaseous Products.								Weight, Solid Residue.										Total Weights.	
	Carbonic anhydride.	Carbonic oxide.	Nitrogen.	Sulphhydric Acid.	Marsh-gas.	Hydrogen.	Oxygen.	Water.	Potassium carbonate.	Potassium sulphate.	Potassium hyposulphite.	Potassium monosulphide.	Potassium sulphocyanate.	Potassium nitrate.	Potassium oxide.	Ammonium sesquicarbonate.	Sulphur.	Water pre-existent.	Gaseous products.	Solid residue.
Powder "A"	·2253	·0529	·1158	...	...	·0022	...	·0225	·5474	·0017	·0048	·0034	...	...	...	·0058	...	·0181	·4187	·5812
,, "B"	·1915	·1014	·1200	...	·0019	·0042	...	·0026	·5296	·0006	·0008	·0006	...	...	...	·0240	...	·0217	·4216	·5773
,, "C"	·2723	·1315	·0875	·0191	·0056	·0011	...	...	·2036	·0042	·0073	·1646	·0187	...	...	·0081	·0627	·0139	·5307	·4692
,, "D"	·2467	·0529	·1188	·0091	·0006	·0011	...	...	·4579	·0230	·0029	·0382	·0005	...	...	·0016	·0352	·0118	·4409	·5591
Cocoa-powder . . .	·2198	·0086	·1049	...	·0004	·0006	...	·0832	·4360	·1332	...	...	...	...	...	...	...	·0133	·4175	·5825
Pebble, W.A., means . .	·2685	·0477	·1123	·0111	·0006	·0006	...	...	·3258	·0710	...	·1042	·0014	·0013	...	·0005	·0445	·0095	·4409	·5496
R.L.G., W.A., means .	·2630	·0422	·1117	·0109	·0008	·0009	·0002	...	·3415	·0844	...	·0807	·0013	·0015	...	·0004	·0490	·0106	·4298	·5591
F.G., W.A., means . .	·2689	·0355	·1123	·0101	·0004	·0007	·0003	...	·2861	·1252	...	·0999	·0007	·0009	·0056	·0003	·0381	·0148	·4282	·5569
Spanish	·2457	·0136	·1108	·0096	...	·0003	·0007	...	·2186	·2975	...	·0473	·0003	·0058	...	·0002	·0431	·0065	·3808	·6127
C. & H. No. 6 . . .	·2593	·0247	·1132	·0083	·0046	·0008	...	...	·3413	·1250	...	·0717	...	·0017	...	·0005	·0372	·0117	·4109	·5774
Mining	·2279	·1522	·0858	·0389	·0070	·0017	...	...	·1945	·0028	...	·1745	·0139	·0004	...	·0084	·0664	·0161	·5135	·4201

Considerations such as are suggested by this table led Sir F. Abel and myself to make a statement which has been somewhat misunderstood, and which has been the subject of a good deal of controversy, viz., that, except for instructional purposes, but little accurate value can be attached to any attempt to give a general chemical expression to the metamorphosis of a gunpowder of normal composition.

Now by this statement, to which, after many years of research, we most emphatically adhere, we did not mean to say that, given precisely the same conditions, the same products would not follow; but we did mean to say that the circumstances under which gunpowder, nominally of the same composition, may be exploded, are so varied—the nascent products may find themselves under such varied conditions both as to pressure, temperature, and the substances with which they find themselves in contact—this last point depending much on the physical characteristics of the powder—that it is not wonderful if considerable variations in the products ensue.

I need only refer in illustration of my remarks to the very interesting decomposition experienced by cocoa-powder. Observe the very small quantity of carbonic oxide, and the large quantity of water formed, while the solid constituents are reduced in number to two.

Let me now call your attention to another point. The table giving the decomposition of gunpowders shows also the ratio between the weights of the solid and gaseous products; but it is necessary that we should know the volume of the gases at ordinary temperatures and pressure. A kilog., then, of these powders, at a temperature of 0° Cent. and a barometric pressure of 760 mm., would give rise to the following quantities of gases:—The numbers in the table expressing litres per kilog., or c.c. per gramme of powder exploded.

TABLE 4.—*Showing the volumes of permanent gases evolved by the combustion of* 1 *gramme of the undermentioned powders.*

	Powder "A."	Powder "B."	Powder "C."	Powder "D."	Cocoa.	Pebble, W.A.	R.L.G., W.A.	F.G., W.A.	Spanish.	C. & H. No. 6.	Mining.
Vols. of gases . .	254	315	347	282	198	278	274	263	234	241	360

That is to say:—Assuming that a kilog. of each of these powders occupied a decimetre cubed, the figures in the table represent for each description of powder the number of similar volumes occupied by the liberated gases when at the temperature and pressure I have named.

I have, in the case of each explosive that I have described, given to you the number of heat-units produced by the explosion. Following the same course with these powders, the number of grm.-units of heat evolved by the combustion of a gramme of each of the powders with which we have experimented is given in Table 5.

TABLE 5.—*Showing the units of heat evolved by the combustion of* 1 *gramme of the undermentioned powders.*

	Powder "A."	Powder "B."	Powder "C."	Powder "D."	Cocoa.	Pebble, W.A.	R.L.G., W.A.	F.G., W.A.	Spanish.	C. & H. No. 6.	Mining.
Units of heat . .	800	715	525	745	837	721	726	738	767	764	517

As in the case of the quantity of gas, so with the heat evolved; there is a great and similar variation in the units of heat, but with this peculiarity—that the powders producing the largest quantity of gas invariably evolve the least quantity of heat.

Take, for example, the last six powders on our list, and observe that in every case the volume of the permanent gases is in inverse ratio to the units of heat evolved. In fact, if, as is done in Table 6, we arrange these six powders in descending order of the number of units of heat, and if we place them also in ascending order of the number of volumes of gas produced, it will be found that we have precisely the same arrangement.

TABLE 6.

Nature of powder.	Units of heat per gramme exploded.	Cubic centimetres of gas per gramme exploded.
Spanish pellet	767·3	234·2
Curtis & Harvey's No. 6 . .	764·4	241·0
W.A.F.G.	738·3	263·1
W.A.R.L.G.	725·7	274·2
W.A. pebble	721·4	278·3
Mining	516·8	360·3

Let me dwell a little longer on this point. Take the powder which has developed the greatest amount of heat—the Spanish. Note that the amount of heat generated is about 50 per cent. greater than that developed by the lowest on the list—the mining. On the other hand, note that the volume of permanent gases evolved by the

mining powder is about 50 per cent. greater than that given off by the Spanish.

The products of the volumes of gas and the units of heat evolved in these powders are nearly the same, and, indeed, the remark may be extended to the other powders in the list, the products of these two numbers not differing very greatly from a constant quantity.

You will anticipate the deduction I am going to draw from these singular facts.

Assume for a moment, for the sake of simplicity, that these six powders have the same composition, but that fortuitous circumstances—their physical condition, for example—have determined the varying quantities of gas evolved, and of heat developed. Assume, further—the assumption approximating to the truth—that the potential energy of all the powders is the same, and we arrive at the conclusion that the smaller number of units of heat, which can be measured by our calorimeter in the case of the mining powder, is due to the larger amount of heat absorbed in placing the much more considerable proportion of the products of combustion in the gaseous condition.

Heat, then, plays the whole *rôle* in the phenomenon. A portion of this heat, to use the old nomenclature, is latent; it cannot be measured by our calorimeter; that is, it has disappeared or been consumed in performing the work of placing a portion of the solid gunpowder in the gaseous condition. A large portion remains in the form of heat, and, as we shall see later, plays an important part in the action of the gunpowder on a projectile.

Turn now to the temperatures and pressures which will be developed when the various explosives we have been considering are fired in a close vessel.

If we suppose the two first explosives described, viz., the mixtures of hydrogen and chlorine and the mixtures of hydrogen and oxygen, to be at atmospheric pressures when fired, both the theoretic temperatures of explosion and the resultant pressures may be affected to some extent by dissociation, which, I need hardly say, acts in the direction of reducing both the temperature and the pressure.

Little or nothing is known of the extent to which dissociation takes place at the very high temperatures produced by the gases we are discussing. That extent, whatever it may be, will doubtless be largely reduced as the tension at which the explosion is carried on is increased.

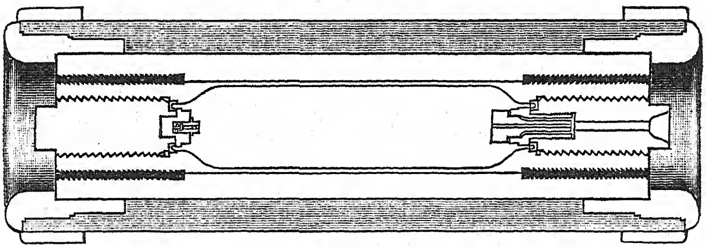
If we suppose no dissociation to take place, and the gases to follow the laws of Boyle and Guy Lussac, a temperature of about 4500° Cent. will be reached by the explosion of the mixture of chlorine and oxygen, and a temperature of about 8000° Cent. by the mixture of hydrogen and oxygen, while the pressures reached will be respectively about 17 and 20 atmospheres.

You will note how feeble are the pressures compared with those with which we have to deal in the case of the explosives to which I now come. The mixed gases could, of course, prior to their detonation, be highly condensed, but the difficulties attending the use of such explosives in the condensed form, whether for artillery or industrial purposes, would be insurmountable.

Before entering upon the temperatures and pressures developed by the explosion of guncotton and gunpowder, as the data I shall lay before you are chiefly derived from experiments made by Sir F. Abel and myself, it may be well to describe, as briefly as possible, some of the apparatus employed by us in our researches.

These diagrams (Figs. 1 and 2) represent two of the vessels

FIG. 1.



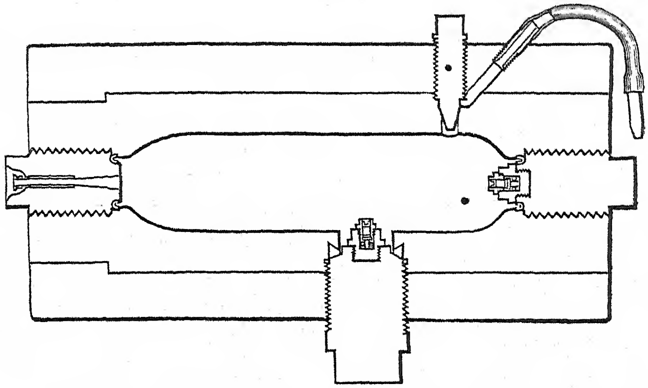
Explosion-vessel for large charges.

in which the explosions were made, one being a very large one, reinforced by steel ribbon, and open at both ends. The two open ends being closed by screw-plugs, the plugs themselves being fitted with special arrangements, with the details of which I need not trouble you, for preventing the escape of gas past the screws of the plugs. In one of the plugs is fitted a small instrument called a crusher-gauge, the object of which is to determine the pressure existing in the chamber at the instant of explosion. In the other plug is fitted an arrangement by which the charge is fired by electricity without any communication with the external air by which the products of explosion can escape.

Although not belonging to my subject, I may here mention a very singular accident which on one occasion happened in using this

vessel, and which explains accidents which have occasionally happened with the B. L. guns. I was experimenting with large charges of powder. The end of the vessel was placed against a

FIG. 2.



Vessel used for experiment with explosives.

wrought-iron beam. The screw—a half-inch pitch—being a very good fit, was screwed into its place with much difficulty, and with the use of a good deal of oil. On firing, the screw unscrewed, I need scarcely say in a very minute part of a second, until the last two threads were reached. These were sheared. Owing to the wrought-iron beam, which, by the way, the canted end of the screw knifed as neatly as if it had been done in a lathe, there was no motion of translation, but the motion of rotation was so high that the screw, first striking the ground and then an iron plate at an angle of 45°, went vertically into the air with a singular humming noise, descending in about 30 seconds a few feet from the place from which it rose.

The accident, unexpected as it was, is not so difficult to understand if you remember that the screw was, so to speak, floating in oil, and that the expansion of the cylinder under the high pressure would remove nearly all the friction I have mentioned.

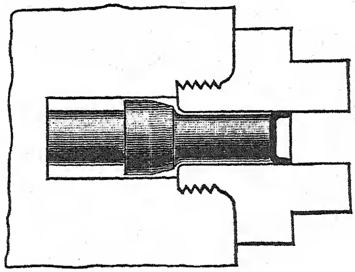
The other vessel is used for smaller charges, and you will observe that on it is shown the arrangement for letting the gases escape, either for the analysis, measurement of quantity, or other purposes.

It may serve to illustrate the progress that has been made in artillery, if I mention that thirty years ago the largest charge then used in any gun was 16 lbs. of powder. The 32-pr. gun, which was the principal gun with which our fleets were armed, fired only 10 lbs.;

but I have fired, and absolutely retained in one of these vessels, no less a charge than 23 lbs. of powder and 5 lbs. of guncotton.

The gauge, which I have called the crusher-gauge, is here shown (Fig. 3). Its action is easily understood. The gas acting on the exposed surface of the piston crushes the copper cylinder on which the piston rests, and by the amount of the crush the value of the pressure can be determined.

FIG. 3.

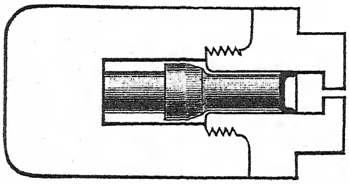


Crusher-gauge.

Under certain circumstances great care is necessary in the use of these gauges.

With guncotton, for example, with large charges, or high density of charge, or when the guncotton is detonated, the products of explosion may be projected with an enormous velocity against the piston. In such a case the pressure indicated would not be the true gaseous pressure—such I mean as would exist were the products of explosion retained in a vessel impervious to heat until the violent waves of pressure generated by the ignition had subsided—but to this true gaseous pressure would be superadded a portion of the energy stored up in the products of explosion, which we may consider in the light of small projectiles striking the gauge and impressing their energy upon it. In our earliest experiments on guncotton, our results, as far as pressure was concerned, were found to be valueless from this cause, and we resorted to various plans to avoid this inconvenience, the most effectual of which is shown here (Fig. 4), the gases being admitted to act on the piston only through an exceedingly small hole, thus shielding the piston from the waves of pressure to which I have alluded.

FIG. 4.



Shielded crusher-gauge.

Even with gunpowder, if the pressures be very high, greater pressures than the true ones may be indicated from the energy imparted to the piston during the space it passes through in crushing the copper, and the most accurate results will be obtained if, prior to the experiment, the coppers be crushed to indicate a pressure a little short of that expected.

In most of the important experiments with guncotton, a crusher-gauge with an unshielded head was placed at the further extremity from the point of ignition. The pressure indicated by this gauge denoted that due to the wave I have described. Two or three other gauges with shielded heads were employed in other portions of the cylinder to indicate the true gaseous pressure.

Let me give an example to show the effect of this arrangement.

A charge of about 3·5 lbs. of guncotton was fired in a cylinder with the crusher-gauges arranged as I have said. Two of the crusher-gauges admitted the gas to the piston through an aperture of only 0·01 inch in diameter; another admitted it through an aperture four times as great, or 0·02 inch in diameter, while the crusher-gauge exposed to the wave-action had its aperture of the full diameter.

The pressures indicated by the first three gauges were respectively 25·6, 26, and 27·1 tons on the square inch, but that given by the gauge at the end of the chamber indicated a pressure of about 45 tons on the square inch, or nearly 7000 atmospheres. On another occasion the pressures indicated by the first three gauges were respectively 32·4, 32, and 33·8 tons per square inch, while the pressure indicated by the gauge exposed to the wave-action was 47 tons.

Again, when a charge of nearly 5 lbs. of guncotton was exploded, the pressures denoted were 45·4, 45·9, and 43·8 tons, while that of the exposed gauge was 54 tons per square inch, or about 8200 atmospheres.

Many more examples might be given, but I must not weary you with dry figures; my object in inflicting so many on you is to show that, where properly protected, the crusher-gauge may be relied upon to give very accordant results.

As might be expected from the very different quantities of heat developed by the explosion of different natures of gunpowder to which I have recently drawn your attention, the temperature at which that explosion takes place likewise varies considerably.

Calculation places the temperature of explosion of ordinary English powder at a little above 2000° Cent., and the direct experiments I have been able to make confirm this estimate. I have submitted to the action of large charges sheet-wire platinum and iridio-platinum. In all cases the platinum showed signs of fusion; in one case—that of a powder known to produce a high temperature—the platinum was completely fused.

The temperature of explosion of guncotton is at least double that of gunpowder, and all the internal apparatus we have used bears

notable signs of the extraordinarily high heat to which they have been exposed, as well as to the extreme violence of the reaction.

Platinum wire and sheet either disappear altogether or are found in minute globules welded on to the surfaces of the apparatus. The internal crusher-gauges and all projecting parts of the apparatus present, when considerable charges are used, have a most extraordinary appearance. The temperature to which the cold surfaces are suddenly exposed develops on the surface a network of minute cracks, which sometimes present the appearance of being filled up with fused steel.

When the charges are very dense, and, owing to that density, the transformation takes place with extreme rapidity, or when the guncotton is exploded by fulminate of mercury, it frequently happens that small portions of the surface are flaked off. Crusher-gauges are sometimes broken transversely, as are also the nozzles of any parts of the apparatus projecting into the chamber.

Portions of the apparatus, in no way exposed to the direct action of the guncotton, are sometimes fractured in the most singular manner; while the correctness of our assumption as to the violence of the internal disturbance—I mean as to the waves of pressure passing from one end of the chamber to the other, and giving rise to local pressure not directly dependent upon the temperature and the volume of gas evolved—is evidenced by the internal gauges always showing unmistakable signs of having been knocked about with great force; a result which does not obtain when gunpowder is the explosive employed.

Crusher-gauges, and other portions of our apparatus that have been damaged as I have described, are on the table.

Let me draw your attention to some of the evils attendant upon a very high temperature of explosion.

I have described to you some of the more striking effects of the high temperature of the explosion of large charges of guncotton on surfaces exposed to its action. But even when these remarkable effects are not shown, as for example when smaller charges are employed, and the cooling influence of large surfaces has more influence, the surfaces still frequently show by minute globules of metal that they have been in a state of fusion, and these indications are quite perceptible with gunpowder as well as with guncotton.

The very high charges now employed (830 lbs. have been fired in a single charge from a 100-ton gun and 300 lbs. from a gun not quite 25 tons in weight), and the relatively very long time during which the high pressure and temperature of the explosion are continued

have aggravated to a very serious extent the evils due to erosion, and the consequent rapid wear of the bores of guns. I have mentioned that at the moment of explosion the surfaces of the gun in the vicinity of the charge are in a state of fusion. You will readily understand that heated gases passing over these fused surfaces at a high velocity and pressure absolutely remove that surface, and give rise to that erosion which is so serious an evil in guns where large charges are employed.

Suppression of windage—that is, making the projectile an exact fit to the bore, does much to diminish, but will not remove erosion altogether. The importance of the subject led Sir F. Abel and myself to make special investigations into the erosive qualities of some of the powders with which we have experimented. As might be expected, the erosive effect varies in a very high degree with the pressure of the eroding gases, but we were hardly prepared for the great difference in erosive effect between powders varying but slightly in the pressures they generated. For example, the powder giving the highest destructive effect eroded steel under the same pressure between three and four times as rapidly as another powder capable of giving to a projectile the same ballistic effect.

The two tubes I hold in my hand show the comparative erosion of precisely similar charges of two several powders. You will have little difficulty, even from where you sit, in observing the difference in their erosive action. Unfortunately, so far, powder-makers have not succeeded in giving us a powder at once suitable for artillery purposes and possessing the non-eroding quality so greatly to be desired.

As you will perhaps surmise, although erosion does not appear simply to depend on the temperature of explosion, the gunpowder which gives the least erosion is that which produces the largest quantity of gas and develops the least heat. With the same temperature of explosion, to avoid serious erosion the pressure should be kept as low as possible; and before leaving this part of my subject it may not be out of place to enumerate one or two of the causes which have made gunpowder so successful an agent for the purposes of the artillerist, which have enabled it, the oldest of all explosives, to hold its own as a propelling agent against the numerous rivals with which modern science has so lavishly furnished us.

In the first place, then, gunpowder, as I have already mentioned, is a mere mixture, not a definite chemical combination. The rapidity of its combustion, it is true, increases very rapidly with the pressure;

but it is free, or nearly so, from that intense rapidity of action, and from those waves of local pressure which are so marked with guncotton, nitro-glycerine, and other kindred explosives, when fired in large charges.

2. The temperature at which the reaction takes place, although absolutely very high, is, if compared with guncotton, for instance, very low; and this, as you will gather from the remarks I have already made, is a point of great importance when the endurance of a gun is taken into account.

It is perhaps hardly necessary for me to say that I am not one of those who advocate or recommend the use of gunpowder giving very high initial tensions. Did we follow such a course, we should lose much and gain little. The bores of our guns would be destroyed in a very few rounds. There is no difficulty in making guns to stand pressures very much higher than those to which we normally subject them, but then they must be in a serviceable condition. Nine-tenths of the failures of guns with which I am acquainted have arisen, not from inherent weakness of the guns when in a perfect state, but from their having, from one cause or another, been in a condition in which they were deprived of a large portion of their initial strength.

If to these considerations I add that with a given weight of gun a higher effect can be obtained, if the maximum pressure be kept within moderate limits, I trust I have said enough to vindicate the correctness of the course which the gunmakers of the world have, so far as I know, without exception followed.

Another advantage possessed by gunpowder over the class of explosives with which I am now comparing it, is the comparative slowness with which the pressure is produced. You are aware that the strength of a structure is much more severely tested when the load or strain to which it is subjected is applied suddenly; so far as my experience goes, guns do not, to any appreciable extent, suffer from the suddenness with which gunpowder tensions are applied, except in a few isolated cases of exaggerated wave-action. But there is no question in my mind that, unless some means of certainly moderating the violence of this action be discovered, both nitro-glycerine and guncotton would from this cause strain the structure of a gun in a higher degree than is due to the pressure actually applied. There is another advantage on which I shall have something to say when I come to the energy developed by gunpowder, and that is, its more uniform action, due to the presence of solid matter in a finely-divided form, which, acting as a source of heat

compensates for the cooling effect due to the work done by the expansion of the permanent gases.

The theoretic pressure developed by guncotton, the whole of the products produced by the explosion being in the gaseous state, is not difficult to calculate. For, having measured by simple means, which I shall not stop to describe to you, the guncotton being first exploded at a high pressure, and the gases suffered to escape into a gasometer, the measured quantity being subsequently reduced to 0° Cent. and 760 mm. pressure, and knowing, at all events approximately, the temperature of explosion, we are in a position to calculate the pressure at any assumed density.

It has been considered by some authorities that, seeing the high temperature at which the explosion of gunpowder, and, in a much higher degree, that of guncotton, takes place, the pressures indicated by theory will be much altered by dissociation. For example, that the carbonic anhydride will be split into carbonic oxide and oxygen. Let me point out that supposing such dissociation to take place, the resultant pressure will, as in every case of dissociation, be much reduced, notwithstanding that at ordinary temperatures and pressures, the carbonic oxide and oxygen occupy a much larger volume than does their combination into carbonic anhydride.

The cause of this reduction of pressure is the heat absorbed by dissociation, and I should not now have alluded to the subject had it not occasionally been assumed that dissociation might increase the pressure of fired gunpowder. This it can never do, and, seeing the influence that pressure may be taken to have in counteracting the effects of temperature with regard to dissociation, Sir F. Abel and I—although it is dangerous to be too dogmatical with respect to reactions occurring under conditions so enormously beyond the range, both as regards temperature and pressure of ordinary experience—are inclined to think that both with regard to guncotton and gunpowder the effects of dissociation, if they exist at all, are practically inappreciable. At all events, the actual pressures as measured, both in the case of guncotton and gunpowder, are certainly not below those required by theory.

Another point requires mention. The explosion of gunpowder is generally, either in the bore of a gun or in a close vessel, extremely rapid; but rapid as it is, when small charges are fired in a large vessel, there is a considerable reduction of pressure from the cooling effect of the vessel, owing to the great difference of temperature between the ignited powder and the vessel.

With guncotton this difference is much more marked, both because the weight of the explosive employed in experiments is much less and the temperature of explosion is much higher.

Between charges of a few ounces and a few pounds, for instance, of the same gravimetric density, there is a very marked difference of pressure.

The actual pressure reached by the explosion of guncottons experimented with by Sir F. Abel and myself, assuming the gravimetric density of the charge to be unity, would be between 18,000 and 19,000 atmospheres, or, say, 120 tons on the square inch.

The pressure I have indicated has not, I need hardly say, been reached in our experiments, both because we should have had great difficulty in making a vessel to stand such pressures, and because charges of such density would not readily be placed in the vessels.

The highest pressure actually recorded with a density of 0·55 was a little over 70 tons on the square inch. The internal gauges were entirely destroyed by the explosion, and the pressure indicated by the gauge which was not destroyed in the vessel itself, is subject to some deduction, due to the energy of the gases to which I have already more than once alluded.

The pressures attained by exploded gunpowder are not nearly so high.

Taking the same density of unity, the pressure in a closed vessel with ordinary powder reaches about 6500 atmospheres, or about 43 tons on the square inch. We have found it possible to measure the pressures due to the explosion of charges of considerably higher density, and have observed pressures of nearly 60 tons with a density of about 1·2, although the great difficulty of retaining the products of explosion of heavy charges of gunpowder—it is far easier to retain the products of explosion of guncotton than of gunpowder—makes the determination a little doubtful.

It is unnecessary to point out the great advantage, when violent explosions or disruptive effects are required, which guncotton and its kindred substances possess over gunpowder; on the other hand, gunpowder has as yet, despite some disadvantages, no competitor which can be compared with it as a propelling agent for artillery purposes; at all events, in cases where large charges are requisite.

We have now found, in the case of each of the four explosives which I have taken as types: First, the volume of the gases developed by the explosion; second, the amount of heat generated; third, the temperature of the various products; fourth, the pressure

existing under given conditions of density. We are, then, now in a position from the known laws of thermo-dynamics to deduce theoretically what will be the energy developed if the products of explosion be allowed to expand to any given extent, and what will be the total work they are capable of performing if suffered to expand indefinitely.

The products of the combustion of the first three of my explosives being practically all gaseous, the same method of calculation would be followed in each case, and as this method in a much more complicated form has also to be employed in considering the expansion of gunpowder in the bore of a gun, I shall, in this part of my subject, confine my remarks to gunpowder as being at once the most difficult, the most suggestive, and the most important.

But before going to the theoretic considerations involved, you may desire to know whether any, and if so, what, experimental means have been adopted to ascertain in a practical manner, the energy developed by an explosive in the bore of a gun.

Now several means have been adopted for this purpose; one method has been to employ a gun of different lengths of bore, and by measuring the velocity of a projectile fired with a given charge from three different lengths, to deduce both the energies and the mean pressures giving rise to these energies.

Another method has been by certain arrangements—by the use, for example, of the crusher-gauges I have described, or by the use of similar instruments placed at different points along the bore—to ascertain by direct measurement the pressure existing at such points, and from these pressures to deduce both the velocity of the projectile and its corresponding energy at these points. The objection to this mode of procedure is that, although the crusher-gauge may, under ordinary circumstances, and with slow-burning powder, be relied upon to give very correct indications of pressure in the powder-chamber, it cannot be relied upon as accurate when the gases or other products of explosion are in rapid motion.

Suppose, for example, a crusher-gauge, or other similar instrument, to be applied at a point near the muzzle of a gun, when the projectile is passing at a very high velocity, say 2000 feet per second. Now it is obvious that the layer of gas in contact with the projectile is endowed with the same high velocity, and if it be diverted so as to act on a pressure-gauge, the pressure-gauge will indicate not only the actual gaseous pressure, but an unknown additional quantity due to the energy of the moving products of combustion.

It was from this cause, aggravated, no doubt, by a defect in his pressure-guage, that Rodman, the pioneer of this mode of investigation, determined pressures, tolerably accurate, in the powder-chamber, but which along the bore were so much in excess of the truth that in some cases his pressures, plotted down so as to form a curve, indicated energies three times as great as those actually developed in the projectile.

A third method followed has been by means of a chronoscope, designed to measure very minute intervals of time, to ascertain the times at which a projectile passes certain fixed points in the bore.

From these data we may deduce the velocities at all points of the bore, and may again from them calculate the pressures necessary to produce them. As the chronoscope that has been used for these experiments has been often described, I shall not detain you by explaining either the mechanical or electrical portions of the instrument, but, as bearing on thermo-dynamics, I may mention an experience in my earlier investigations with this instrument which may be new to you, as it then was to me. I wished to dispense with the toothed gear for driving certain discs, and I had imagined if two sheaves or pulleys of equal size were connected by a belt so arranged that the belt would not slip on either sheave, that the two pulleys must then be rotating with the same angular velocity. Such, however, is by no means the case. In my own experiments the velocities differed greatly. I supposed the fact to be altogether new, but, as sometimes happens to most investigators, afterwards found that the anomaly had been before observed, and was due to the elasticity of the driving-belt I used, and that the work impressed on the driving-wheel, but not communicated to the driven, was transformed into heat absorbed by and dissipated from the belt.

Returning now to the experimental methods I have described, I may say shortly, that the whole of them have been followed, and the results obtained, subject to some anomalies which I shall stop neither to describe nor explain, have been carefully compared, and have been found to agree in a most remarkable manner with the results indicated by theory.

And, for the sake of clearness, let me recapitulate the problem with which we have to deal. Suppose a charge of gunpowder placed in the chamber of a gun. Suppose the gravimetric density of the charge to be unity, that it is fired, that it be completely exploded before the shot be allowed to move, what, immediately prior to the

shot being permitted to move, is the state of things in the powder-chamber?

Roughly speaking, it is as follows:—

The products of explosion are divided into two classes of substances, about two-fifths by weight of the powder being in the form of permanent gases and three-fifths solid matter, the solid matter being perfectly liquid at the moment of explosion, and in an extremely fine state of division. By the combustion is generated some 730 units of heat. The temperature of the explosion is about 2200° Cent., or about 4000° Fahr., and the exploded powder exercises a pressure of about 6500 atmospheres, or about 43 tons per square inch, against the walls of the chamber and against the projectile.

Let us now suppose that the projectile which we have hitherto supposed to be rigidly fixed, is allowed to move; that is, that the products of combustion are suffered to expand, and let us consider what are the relations existing between the density of the gases, the pressure they exert, and the velocity of the projectile.

The first person who attempted to solve this question was Hutton. He, however, supposed, as it was not unnatural to do in the then state of knowledge, that the tension of the inflamed gases was directly proportional to their density and inversely as the space occupied by them. In other words, he supposed that the expansion of the gases, while performing work, was effected without expenditure of heat.

De Saint Robert, the first to apply to artillery the modern theory of thermo-dynamics, corrected Hutton's error, but, like Hutton, he supposed that the whole of the products of combustion were in a gaseous state, and as such doing work on the projectile.

Bunsen and Schischkoff, and their classical researches on gunpowder, pointed out that though a slight volatilisation of the solid products could not be denied, yet that it was in the highest degree improbable that the tension of such vapours would ever reach a single atmosphere, much less affect the pressures in any appreciable degree.

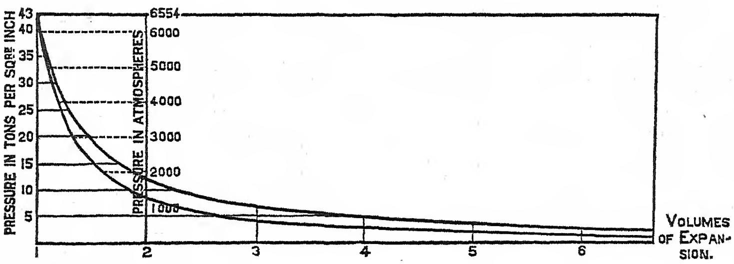
They therefore assumed that the work done on the projectile was due to the expansion of the gaseous products alone, without addition or subtraction of heat.

In the researches made by Sir F. Abel and myself, when we found that the pressures in the bores of guns, and the energies generated by gunpowder, were far in excess of those deduced from Bunsen and Schischkoff's theory, we came to the conclusion that this

difference was due to the heat stored up in the solid, or rather the liquid, products of combustion. In fact, these products, forming as they do with ordinary English gunpowder nearly three-fifths of the weight of the powder, being also in a state of very minute division, constitute a source of heat of a very perfect character, and are available for compensating the cooling effect due to the expansion of the gases on the production of work.

The formula expressing the relation between the pressure and the volume under these new conditions is of a rather complicated character, and instead of giving it to you, I have placed on this diagram (Fig. 5) a curve showing the relation between the tension and the density of the products of combustion when employed in the production of work; and by way of showing you how important a part is played by the heat stored up in the solid residue, I have

FIG. 5.



Curves showing pressure and work developed by expansion of gunpowder, lower curve denoting the pressure on Bunsen and Schischkoff's hypothesis.

placed on the same diagram a curve showing the tension and the density calculated on Bunsen and Schischkoff's hypothesis; that is, that the energy of the projectile is due to the expansion of the gaseous products alone, without addition or subtraction of heat.

You will observe that in this diagram the tension is represented by the ordinates, the expansions by the abscissæ, and the energy developed by any given expansion is denoted by the area between the corresponding ordinates, the curve and the axis of abscissæ.

If this theoretic curve be compared with the curve deduced from experiments in the bores of guns, after the charge may be supposed to be completely consumed, the agreement is most remarkable, and affords ample evidence of the approximate correctness of the theory. Were the curve derived from experiment to be laid down on this diagram, the curves, after, as I have said, complete combustion, may be assumed to have taken place, are scarcely distinguishable.

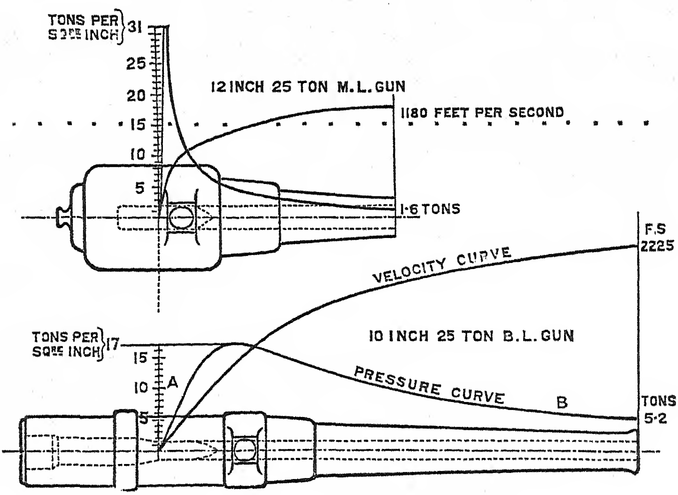
In an earlier part of my lecture I stated that I could not agree with those who are in favour of the strongest—meaning by the term the most explosive—powder manufactured.

To show you the advance that has been made by moving in exactly the opposite direction, I have exhibited on this diagram (Fig. 6) two guns of precisely the same weight, but differing in date by an interval of ten years. One of these guns is designed to fire the old-fashioned R. L. G.; the other, modern powders.

Observe the difference in the appearance of the guns and in the thickness over the powder-charge.

These curves, you will note, represent the gaseous pressure at

FIG. 6.



Comparison between early rifled and modern rifled guns.

any point in the passage of the projectiles through the bore, and their areas represent the total energies developed.

Observe the difference. The maximum pressure in the older is nearly double that in the modern gun, while the velocity developed by the latter is twice, and the energy not far from three times, that of the former; and if we take the foot-tons per inch of shots' circumference to represent approximately the respective penetrating powers of the projectiles, the superiority of the modern gun is still more apparent.

I am bound, however, to call your attention to one point. The new gun is, as a thermo-dynamic machine, much less efficient than the old. You will observe that the charge used with the new gun is

just four times that of the old, while the energy realised is barely three times as great. This arises chiefly from the fact that although the 10-inch gun is absolutely much longer than its rival, it is, taken in relation to the charge, much shorter; that is, the gases are discharged at the muzzle at a much higher tension.

If the modern gun were lengthened so that the products of combustion were discharged at the same tension, the difference in efficiency would be insignificant; and this you can readily understand, since, if we suppose the maximum tension in the modern gun increased to correspond with that in the old, the area indicated in the diagram would represent the additional energy to be realised by the use of an explosive powder; but this additional energy would be dearly purchased by the necessity of having to double the strength of the gun over the long space occupied by the powder-charge, and the same energy could be obtained in a much more economical way by adding 2 or 3 calibres to the length of the gun.

There is another point that must not be lost sight of. In my remarks on the explosion of guncotton, I drew attention to the effects which followed the waves of pressure resulting from the high velocity of the ignited products. With highly explosive powders, especially in long charges, similar effects are observed, and in such cases pressures have been registered very greatly above those due to the normal action of the charge, while these abnormal pressures act during so short a time, that they produce an almost inappreciable effect upon the motion of the projectile.

The temperature of the gases of course suffers a considerable reduction during the expansion in the bore. If we suppose such a gun as I have been just describing impervious to heat, the loss of heat due to the work done would be about 400° Cent. It would be much greater were it not for the heat stored up in the non-gaseous products of combustion.

It remains to consider the total amount of energy stored up in our explosives.

For the first three we have discussed, the calculation is not difficult. Knowing the permanent gases formed, knowing also their specific heats at constant pressure and volume, the ordinary laws of thermo-dynamics enable us to calculate the total energy which will be developed.

In the case of the most important, gunpowder, the calculation is, as I have already pointed out, somewhat complicated by the non-gaseous products. But with this correction, the calculation for

gunpowder also is reducible to the same law. (*Reverting to the diagram.*)

I have shown you that the energy available for any given expansion of a given weight of gunpowder is represented by the area contained between the curve, the axis of abscissæ and two ordinates, the initial, and that corresponding to the density at which the products of combustion are discharged from the gun.

The total energy obtainable if the charge be indefinitely expanded is represented by the area contained between the ordinate representing the initial pressure, the curve AB, and the axis of abscissæ, which is a tangent to AB at infinity.

Some interesting points may be noted in connection with the work developed by gunpowder.

The total energy stored up in gunpowder is about 340,000 kilogrammetres per kilogramme of powder, or in English measure, a little under 500 foot-tons per lb. of powder.

If we compare this potential energy of 1 lb. of gunpowder with that stored up in 1 lb. of coal, we are—perhaps not unnaturally, being accustomed to the enormous pressures developed by gunpowder—somewhat astonished at the results of our comparison.

The potential energy of 1 lb. of gunpowder is as nearly as possible $\frac{1}{10}$ of that of 1 lb. of coal, and $\frac{1}{40}$ of that of 1 lb. of hydrogen. It is not even equal to the energy stored up in the carbon which forms one of its own constituents.

In making this comparison, however, one important point must not be forgotten. Gunpowder and other kindred explosives have stored up in them the oxygen necessary for the oxidation of their carbon and other oxidisable substances, while 1 lb. of carbon in burning to carbonic acid has to draw from the air nearly 3 lbs. of oxygen, and 1 lb. of hydrogen takes 8 lbs. of oxygen.

Many persons, deceived by the high pressures developed by gunpowder, have imagined that this or other similar explosives might be utilised as a motive-power, but the comparison I have made will have convinced you of the futility of any such attempts in an economical point of view.

For though, as I have stated, gunpowder contains the oxygen necessary for its own combustion, such oxygen is in a most expensive form, while the oxygen consumed by coal, being derived from the air, costs nothing; and if we take gunpowder as two hundred times more costly than coal, and as possessing only one-tenth of its potential energy, it follows that as an economic

source of power coal has the advantage by at least two thousand to one.

I have stated that the total theoretic work of gunpowder is a little under 500 foot-tons per lb. of powder, but you may desire to know what proportion of this theoretic work is realised in modern artillery.

Dependent upon conditions with which I need not trouble you, the actual energy realised by modern guns varies from about 50 to a little over 90 foot-tons per lb. of powder, or, let us say, from about a tenth to about a fifth of the total theoretic effect. The total theoretic effect, you will remember, supposes infinite expansion, but if we compare the energy expressed in the projectile with that due to the expansion of the gases, we shall find that since a gun is an extremely simple form of a thermo-dynamic engine, the coefficient of effect is high. The average may, I think, be taken somewhere about 80 per cent. It rarely falls below 70 per cent., and is occasionally, with large guns and charges, considerably above 90 per cent.

But I must conclude both my own lecture and the series for this year.

I regret that it has not fallen to the lot of an abler and more practised lecturer to give the concluding lecture of a course on so important and interesting a subject as that upon which my predecessors and I have addressed you. None can be more painfully aware than I am that I have been unable to make my lecture worthy either of my subject or my audience, and I can only plead, in extenuation, that I had no idea that I was to be called upon until I saw my name announced to give the concluding lecture of the course, and that business claims have utterly prevented my giving the time to the subject which its importance demands.

Were it necessary to urge upon your attention the claims of the modern science of thermo-dynamics, I might take, as perhaps the most striking instance, the progress of artillery during the last quarter of a century.

Twenty-five years ago our most powerful piece of artillery was a 68-pr., throwing its projectile with a velocity of 1570 feet per second.

Now the weight of our guns is increased from 5 tons to 100, the projectile from 68 lbs. to 2000, the velocities from 1600 feet to 2000 feet, the energies from 1100 foot-tons to over 52,000 foot-tons.

Large as these figures are, and astonishing as are the energies which in a small fraction of a second we are able to impress on a projectile of nearly a ton weight, they sink into the most absolute

insignificance when our projectiles are compared with other projectiles, velocities, and energies existing in nature, and with which we find ourselves surrounded.

Helmholtz has given an estimate somewhere of the heat that would be developed if our earth were suddenly brought to rest, but if, looking at our earth in an artillery point of view, and following the principles I have to-night laid down, we considered our earth as an enormous projectile, and if we supposed further, that we could utilise the whole energy stored up in gunpowder, we should yet require a charge 150 times greater than its own weight, or 900 times greater than its volume, to communicate to the earth her motion in her orbit.

It only remains to me to thank you for the attention with which you have listened to a lecture which, from its technical nature, must necessarily be somewhat dry and uninteresting.

VIII.

MECHANICAL SCIENCE IN RELATION TO THE NAVAL AND MILITARY SERVICES

(*Address to the Mechanical Science Section of the British Association, Leeds*, 1890.)

IN taking over the Chair of this Section from my distinguished predecessor, I cannot but feel myself to some extent an intruder into the domain of mechanical science, and I am conscious that the office which I have the honour to hold would have been more worthily filled by one of the great mechanicians who have won for the town in which we hold our meeting so widespread a reputation.

I can truly say the claims on my time are so considerable that I should not have ventured to appear before you in the character of President of this Section, had it not been for my desire to afford what little support might be in my power to my friend the President of the British Association, with whom for so long a period I have been associated by so many ties.

I believe I should have consulted best both my own feelings and your patience by merely opening the Section in a formal manner, and proceeding at once to the business of the meeting. One of my predecessors, however, has pointed out that Sir F. Bramwell, whose authority is too great to be disputed, has ruled that to depart from the time-honoured practice of an address is an act of disrespect to the Section—a ruling which has, without cavil, been accepted.

I therefore propose to direct your attention, by a few brief remarks, to that branch of mechanical science with which I am best acquainted. I shall endeavour to show the great indebtedness of the naval and military services to mechanical science during the period with which I have been more or less connected with them, and the complete revolution which has in consequence resulted in every department and in every detail.

But before commencing with my special subject, it is impossible that I should pass over in silence the great work which has excited so much interest in the engineering world, and which, since we last met, has, with formalities worthy of the occasion, been opened by H.R.H. the Prince of Wales.

It is in no way detracting from the merit of the distinguished engineers who have with so much boldness in design, with such an infinity of care in execution, with so much foresight in every detail, given to the country this great monument of skill, if I venture to point out that, without the great advance of mechanical and metallurgical science during the present generation, and the co-operation of a host of workers, a creation like that of the Forth Bridge would have been an impossibility.

The bridge has been so frequently and so fully described that it is unnecessary in this address I should do more than draw your attention to some of its main features.

The bridge, with its approach-viaducts, has a total length of 8296 feet, or nearly a mile and six-tenths; and this length comprises two spans of 1710 feet, two of 680½ feet, fifteen of 160 feet, four of 57 feet, and three of 25 feet.

The deepest foundation is 90 feet below high-water mark, and the extreme height of the central position of the cantilever is 361 feet above the same datum, making the extreme total height of the bridge 451 feet.

The actual minimum headway in the channels below the centre of the main spans at high-water spring tides is a little over 150 feet, and the rail level is about 6 feet higher.

The weight of steel, nearly all riveted work, is 54,076 tons, and the amount of masonry and concrete 4,057,555 cubic feet.

It is difficult, even for experts, fully to appreciate the stupendous amount of work indicated by these figures. During the Paris Exhibition the Eiffel Tower justly excited considerable admiration, and brought its designer into much repute; but that great work sinks altogether into insignificance when compared with the Forth Bridge.

Conceive, as I have heard described, the Eiffel Tower built, not vertically, but horizontally; conceive it further built without support, and at a giddy height over an arm of the sea. Such a work would do little more than reach half across one of the main spans of this great bridge.

Those only who have had work of a similar nature can fully appreciate the innumerable experiments that must have been made,

and the calculations that must have been gone through to secure the maximum attainable rigidity both with respect to the strains induced vertically by the railway traffic and its own weight, and horizontally by the force of gales.

The anxiety as to the security of the erection might well daunt the most skilful engineer. We are told that, apart from the permanent work, many hundreds of tons of weight in the shape of cranes, temporary girders, winches, steam boilers, rivet furnaces, and riveting machines, miles of steel-wire rope, and acres of timber staging were suspended from the cantilevers. A heavy shower of rain would in a few minutes give an additional weight of about 100 tons; and in their unfinished state, while approaching completion, the force of any gale had to be endured.

I trust that as the Forth Bridge has been a great engineering, it may likewise prove a financial success, and I feel sure that all who hear me are rejoiced that it has pleased Her Majesty to confer the distinguished honours she has awarded to Sir John Fowler and Sir B. Baker—honours, I may add, that have rarely been more worthily bestowed.

Let me turn now to the subject on which I propose to address you; and I shall first advert to the change which within my own recollection has taken place in that service which has been the pride and glory of the country in time past, and on which we must rely in the future as our first and principal means at once of defence and attack.

To give even an idea of the revolution which our navy has undergone, I must refer in the first instance to the navy of the past. I must refer to those vessels which in the hands of our great naval commanders won for England victories which left her at the close of the great wars supreme upon the sea.

A "first-rate" of those days (I will take the *Victory* as a type) was a three-decker, 186 feet in length, 52 in breadth, with a displacement of 3500 tons; she carried an armament of 102 guns, consisting of thirty 42- and 32-prs., thirty 24-prs., forty 12-prs., and two 68-pr. carronades (the heaviest of her guns was a 42-pr.), and she had a complement of nearly 900 men. When we look at the wonderful mechanism connected with the armaments of the fighting-ships of the present day, it is difficult to conceive how such feats were accomplished with such rude weapons.

With the exception of a few small brass guns, the guns were mere blocks of cast iron, the sole machining to which they were subjected consisting in the formation of the bore and the drilling of the vent.

A large proportion of nearly every armament consisted of carronades—a piece which was in those days in great favour. They threw a shot of large diameter from a light gun with a low charge, and their popularity was chiefly due to the rapidity with which they could be worked. The great object of every English commander was, if it were possible, to bring his ship alongside that of the enemy; and under these circumstances the low velocity given by the carronades became of comparatively small moment, while the ease of working and the large diameter of the shot were factors of the first importance.

The carriages on which the rude weapons I have described were placed, were themselves, if possible, even more rude. They were of wood, and consisted of two cheeks with recesses for the trunnions, which were secured by cap squares, the cheeks being connected by transoms and the whole carried on trucks. The gun was attached to the vessel's side, and the recoil was controlled by breeching. The elevation was fixed by quoins which rested on a quoin bed, and handspikes were used either for elevating or for training.

It is obvious that to work smartly so rude a machine a very strong gun's crew was required. Indeed, the gun and its carriage were literally surrounded by its crew, and I may refer those who desire to acquaint themselves with the general arrangements of what was once the most perfect fighting-machine of the first navy in the world, to the frontispiece of a book now nearly forgotten—I mean Sir Howard Douglas's *Naval Gunnery*.

The mechanical appliances on board these famed war-vessels of the past were of the simplest possible form, and such as admitted of rapid renewal or repair. There was no source of power except manual labour; but, when handled with the unrivalled skill of British seamen, the handiness of these vessels and the precision with which they were manœuvred was a source of never-ending admiration.

Those who have seen, as I have done, a fleet like the Mediterranean squadron enter a harbour such as Malta under full sail, and have noted the precision with which each floating castle moved to her appointed place, the rapidity with which her canvas was stowed, have seen a sight which I consider as the most striking I have witnessed, and infinitely more imposing than that presented under like circumstances by modern vessels, any one of which could in a few minutes blow out of the water half-a-dozen such men-of-war as I have been just describing.

I must not, however, omit to mention two advantages possessed by the old type of war-vessels, which, if we could reproduce them,

would greatly please modern economists. I mean, their comparatively small cost, and the length of time the vessels remained fit for service.

When the *Victory* fought the battle of Trafalgar she had been afloat for forty years, and her total cost, complete with her armament and all stores, was probably considerably under £100,000. The cost of a first-rate of the present day, similarly complete, would be nearly ten times as great.

The most improved battle-ships of the period just anterior to the Crimean war differed from the type I have just described, mainly by the addition of steam power, and for the construction of these engines the country was indebted to the great pioneers of Marine Engineering, such as J. Penn & Sons, Maudslay Sons & Field, Ravenhill Miller & Co., Rennie Bros., etc., not forgetting Messrs Humphreys & Tennant, whose reputation and achievements now are even more brilliant than in these earlier days.

Taking the *Duke of Wellington*, completed in 1853, as the type of a first-rate just before the Crimean war, her length was 240 feet, her breadth 60 feet, her displacement 5830 tons, her indicated horse-power 1999, and her speed on the measured mile 9·89 knots. Her armament consisted of 131 guns, of which thirty-six 8-inch and 32-prs. were mounted on the lower deck, a similar number on the middle deck, thirty-eight 32-prs. on the main deck, and twenty short 32-prs. and one 68-pr. pivot-gun on the upper deck.

Taking the *Cæsar* and the *Hogue* as types of second- and third-rate line-of-battle ships, the former, which had nearly the displacement of the *Victory*, had a length of 207 feet, a breadth of 56 feet, and a mean draught of 21. She had 1420 indicated horse-power, and her speed on the measured mile was 10·3 knots. Her armament consisted of twenty-eight 8-inch guns and sixty-two 32-prs., carried on her lower, main, and upper decks. The *Hogue* had a length of 184 feet, a breadth of 48 feet 4 inches, a mean draught of 22 feet 6 inches; she had 797 indicated horse-power, and a speed of $8\frac{1}{3}$ knots. Her armament consisted of two 68-prs. of 95 cwt., four 10-inch guns, twenty-six 8-inch guns, and twenty-eight 32-prs. of 56 cwt.—sixty guns in all.

Vessels of lower rates (I refer to the screw steam frigates of the period just anterior to the Crimean war) were, both in construction and armament, so closely analogous to the line-of-battle ships that I will not fatigue you by describing them, and will only allude to one other class, that of the paddle-wheel steam frigate, of which I may

take the *Terrible* as a type. This vessel had a length of 226 feet, a breadth of 43 feet, a displacement of about 3000 tons, and an indicated horse-power of 1950. Her armament consisted of seven 68-prs. of 95 cwt., four 10-inch guns, ten 8-inch guns, and four light 32-prs.

It will be observed that in these armaments there has been a very considerable increase in the weight of the guns carried. As I have said, the heaviest guns carried by the *Victory* were the 42-prs. of 75 cwt., but in these later armaments the 68-pr. of 95 cwt. is in common use, and you will have noted that the carronades have altogether disappeared. But as regards improvements in guns or mounting, if we except the pivot-guns, with respect to which there was some faint approach to mechanical contrivance to facilitate working, the guns and carriages were of the rude description to which I have alluded.

In one respect, indeed, a great change had been made. Shell-fire had been brought to a considerable state of perfection, and the importance ascribed to it may be traced in the number of 10-inch and 8-inch shell-guns which entered into the armaments of the *Duke of Wellington* and the other ships I have mentioned. Moorsom's concussion fuse and other similar contrivances lent great assistance to this mode of warfare, and its power was soon terribly emphasised by the total destruction of the Turkish squadron at Sinope by the Russian fleet. In that action shell-fire appears to have been almost exclusively used, the Russians firing their shell with rather long time fuses in preference to concussion, with the avowed object of there being time before bursting to set fire to the ship in which they lodged.

It is curious to note in the bygone discussions relative to shell-fire the arguments which were used against it; among others it was said that the shell would be more dangerous to those who used them than to their enemies. There was some ground for this contention, as several serious catastrophes resulted from the first attempts to use fused shells. Perhaps the most serious was that which occurred on board H.M.S. *Theseus*, when seventy 36- and 24-pr. shells captured from a French store ship and placed on the quarter-deck for examination exploded in quick succession, one of the fuses having by some accident been ignited. The ship was instantly in flames; the whole of the poop and after-part of the quarter-deck were blown to pieces. The vessel herself was saved from destruction with the greatest difficulty, and forty-four men were killed and forty-two wounded.

This accident was due to a neglect of obvious precaution which would hardly occur nowadays, but I have alluded to the circumstance because the same arguments, or arguments tending in the same direction, are in the present day reproduced against the use of high explosives as bursting-charges for shells. To this subject I myself and my friend and fellow-labourer, Mr Vavasseur, have given a good deal of attention, and the question of the use of these shells and the best form of explosive to be employed with them is, I believe, receiving attention from the Government. The importance of the problem is not likely to be overrated by those who have witnessed the destruction caused by the bursting of a high explosive shell, and who appreciate the changes that by their use may be rendered necessary, not only in the armaments, but even in important constructional points of our men-of-war.

Shortly before the termination of the long period of peace which commenced in 1815, the attention of engineers and those conversant with mechanical and metallurgical science, seems to have been strongly directed towards improvements in war material. It may easily be that the introduction of steam into the navy may have had something to do with the beginning of this movement, but its further progress was undoubtedly greatly accelerated by the interest in the subject awakened by the disturbance of European peace which commenced in 1854.

Since that date—whether we have regard to our vessels of war, the guns with which they and our fortresses are armed, the carriages upon which those guns are mounted, or the ammunition they employ—we shall find that changes so great and so important have been made that they amount to a complete revolution. I believe it would be more correct to say several complete revolutions. It is at least certain that the changes which were made within the period of ten years following 1854 were far more important and wide-spreading in their character than were all the improvements made during the whole of the great wars of the last and the commencement of the present century.

Indeed, it has always struck me as most remarkable that during the long period of the Napoleonic and earlier wars, when the mind of this country must have been to so large an extent fixed on everything connected with our naval and military services, so little real progress was made.

Our ships, no doubt, were the best of their class, although, I believe, we were indebted for many of our most renowned models to

vessels captured from our neighbours. They were fitted for sea with all the resources and skill of the first seamen of the world, and when at sea were handled in a manner to command universal admiration. But their armaments were of the rude nature I have described, and so far as I can see possessed little, if any, advantage over those nearly a couple of centuries earlier. It is not improbable that the great success which attended our arms at sea may have contributed to this stagnation.

The men who with such arms achieved such triumphs may well be forgiven for believing that further improvement was unnecessary; and it must be remembered that the practice of engaging at very close quarters minimised to a great extent the most striking deficiencies of the guns and their mountings.

I need scarcely, however, remind you that were two vessels of the old type to meet, one armed with her ancient armament, the other with modern guns, it would be vain for the former to attempt to close. She would be annihilated long before she approached sufficiently near to her antagonist to permit her guns to be used with any effect.

It would be quite impossible, within reasonable limits of time, to attempt to give anything like an historical account of the changes which have taken place in our ships of war during the last thirty-five years, and the long battle between plates and guns will be fresh in the memory of most of us. The modifications which the victory of one or the other impressed on our naval constructions are sufficiently indicated by the rapid changes of type in our battle-ships, and by the number of armour-clads once considered so formidable, but seldom now mentioned except to adorn the tale of their inutility. The subject also requires very special knowledge, and to be properly handled must be dealt with by some master of the art, such as our Director of Naval Construction.

Let me now compare with the vessels of the past those of the present day, and for my purpose I shall select for comparison as first-rates the *Victoria* and the *Trafalgar*. The *Victoria* has a length of 340 feet, a breadth of 70 feet; she has a displacement of about 10,500 tons, an indicated horse-power of 14,244, and she attained a speed on the measured mile of 17½ knots; she has a thickness of 18 inches of compound armour on her turrets, a similar thickness protects the redoubt, and her battery-deck is defended with 3-inch plates. Her armament consists of two 16¼-inch 110-ton guns, one 10-inch 30-ton gun, twelve 6-inch 5-ton guns, twelve 6-pr. and nine 3-pr. quick-firing guns, two machine-guns, and six torpedo-guns.

The *Trafalgar* has a length of 345 feet, or very nearly double the length of the *Victory*, a displacement of 12,000 tons, an indicated horse-power of 12,820, and a speed on the measured mile of a little over $17\frac{1}{4}$ knots. Her armament consists of four 68-ton guns, six 4·7-inch quick-firing guns, six 6-pr. and nine 3-pr. quick-firing guns, six machine- and six torpedo-guns.

Comparing the armament of the *Victoria* with that of the *Victory*, we find, to quote the words of Lord Armstrong—which when evaluating the progress we have made will bear repetition—that while the heaviest gun on board the *Victory* was a little over 3 tons, the heaviest on board the *Victoria* is a little over 110 tons. The largest charge used on board the *Victory* was 10 lbs., the largest on board the *Victoria* close on 1000 lbs.; the heaviest shot used in the *Victory* was 68 lbs., in the *Victoria* it is 1800 lbs. The weight of metal discharged from the broadside of the *Victory* was 1150 lbs., from that of the *Victoria* it is 4750 lbs. But having regard to the energy of the broadside, the power of each ship is better indicated by the quantity of powder expended than by the weight of metal discharged, and while the broadside fire from the *Victory* consumed only 355 lbs. of powder, that from the *Victoria* consumes 3120 lbs.

These figures show in the most marked manner the enormous advances that have in every direction been made in the construction and armament of these marine monsters; but it is when we come to the machinery involved in our first-rates that the contrast between the past and the present is brought most strongly into prominence.

I have alluded to the simplicity of the arrangements on board the old battle-ships, but no charge of this nature can be made against the present. The *Victoria* has no less than twenty-four auxiliary steam-engines in connection with her main engines, viz., two starting, two running, eight feed, eight fan for forced draught, and four circulating water engines. She has in addition thirty steam-engines unconnected with her propelling engines, viz., six fire and bilge engines, two auxiliary circulating engines, four fan engines for ventilating purposes, two fresh-water pumping engines, two evaporative fuel engines, one workshop, one capstan, and five electric-light engines, four air-compressing and three pumping engines for hydraulic purposes.

She has further thirty-two hydraulic engines, including two steering engines, four ash-hoisting engines, two boat engines, four ammunition lifts, two turret-turning engines, one topping winch, two transporting and lifting engines, two hydraulic bollards, and fourteen other engines for performing the various operations necessary for the

working of her heavy guns, making a grand total of eighty-eight engines. This number is exclusive of the machinery in the torpedo and other steam boats, and of the locomotive engines in the torpedoes carried, which are themselves engines of a most refined and delicate character.

At an earlier point in my address I alluded to the incomparable seamanship of our bygone naval officers. Seamanship will, I fear, in future naval battles no longer play the conspicuous part it has done in times past. The weather gage will belong, not to the ablest sailor, but to the best engineer and fastest vessel; but the qualities of pluck, energy, and devotion to their profession which distinguished the seamen of the past have, I am well assured, been transmitted to their descendants, and I am glad to have the opportunity of expressing my admiration of the ability and zeal with which the naval officers of the present day have mastered, and the skill with which they use, the various complicated, and in some cases delicate, machinery which mechanical engineers have placed in their hands.

I pass now to a class of vessels—the fast, protected cruisers—intended to take the place and perform the duties of the old frigates. Of these I will take as types H.M.S. *Medusa* and the Italian cruiser *Piemonte*. The *Medusa* has a length of 265 feet, a breadth of 41 feet, a displacement of 2800 tons, and her engines have 10,010 indicated horse-power. Her armament consists of six 6-inch breech-loading guns, ten 3-prs., four machine-guns, and two fixed and four turning torpedo tubes. The *Piemonte* has a length of 300 feet, a breadth of 38 feet, a displacement of 2500 tons, and her engines of 12,981 indicated horse-power developed on the measured mile a speed of 22·3 knots, or about 26 miles. Her armament, remarkable as being the first instance of an equipment composed altogether of quick-firing guns, consists of six 6-inch 100-prs., and six 4·7-inch 45-prs., all with large arcs of training, ten 6-pr. Hotchkiss, four Maxim-Nordenfelt machine-guns, and three torpedo-guns.

These vessels have a steel protective deck, with sloping sides from stem to stern, protecting the vitals of the ship; above and below the armour deck the vessels are subdivided into a large number of watertight compartments, and a portion of the vessel's supply of coal is employed to give additional protection.

With respect to the *Piemonte*, the engines (vertical triple-expansion) were designed and constructed by Messrs Humphreys, Tennant, & Co. They are, in order that they may be wholly below the water-line, of exceedingly short stroke (27 inches), and the

behaviour of the engines, both on their trials here and in the very severe weather to which the vessel was exposed on her passage out, amply justify these eminent engineers in their somewhat bold experiment.

I might describe other cruisers, both larger and smaller than those I have selected, but I must not fatigue you, and will only in this part of my subject draw your attention to these triumphs of engineering ingenuity and skill, I mean the torpedo boats, which (whether or not locomotive torpedoes continue to hold their own as engines of destruction), are destined, I believe, to play no insignificant part in future naval warfare.

Let me illustrate the marvels that have been achieved by the great English engineers who have brought these vessels to their present state of perfection, by giving you a few particulars concerning one or two of them.

A first-class torpedo boat by Yarrow has a length of 135 feet, a breadth of 14 feet, a displacement of 88 tons, and with engines of 1400 indicated horse-power attains a speed of a little over twenty-four knots.

A slightly larger boat, built for the Spanish Government by Thorneycroft, has a length of 147 feet 6 inches, a breadth of 14 feet 6 inches, and with engines of 1550 indicated horse-power, has attained a speed of a little over twenty-six knots.

It is interesting to note that the engines of the first-named torpedo boat develop nearly exactly the same power as those of the 90-gun ship, the *Cæsar*, and the engines of the second-named but little less than that developed by the *Duke of Wellington;* two vessels which, you will remember, I have taken as types of the second- and first-rate men-of-war of thirty-five years ago.

The weight of the engines of the *Duke of Wellington* and the *Cæsar* would be approximately 400 tons and 275 tons, while that of the torpedo boats is about 34 tons.

But if these results are sufficiently remarkable, the economy attained in the consumption of coal is hardly less striking.

The consumption of coal in the early steam battle-ships was from 4 to 5 lbs. per indicated horse-power per hour, and occasionally nearly reached 8 lbs.

At the present time in good performances the coal consumption ranges from $1\frac{1}{2}$ to $1\frac{3}{4}$ lbs. per indicated horse-power per hour under natural draught, and from 2 to $2\frac{1}{4}$ lbs. per hour with forced draught.

In war-ships the engines are designed to obtain the highest

possible power on the least possible weight, and this for a comparatively short time, and, further, have to work at such various powers, that the question of economy must be a secondary consideration.

With the different conditions existing in the mercantile marine, more economical results may be expected, and I believe I shall not be far wrong in assuming that in special cases $1\frac{1}{3}$ lb. may possibly have been reached; but I have not been able to obtain exact information on this head.

Turning now to the guns, let me refer first to those which were in use thirty-five years ago, and which formed the armaments of the ships of those days, and of the fortresses and coast defences of the United Kingdom and colonies.

The whole of these, with the exception of a few very light guns, were made of cast iron. I have already alluded to the small amount of machine-work (not of a very refined character) expended on them. Although the heaviest gun in use was only a 68-pr., there were no less than sixty different natures of iron ordnance. Of the 32-pr. alone there were as many as thirteen descriptions, varying in length and weight. Of these thirteen guns, again, there were four separate calibres, ranging from 6·41 inches to 6·3 inches, and as the projectile was the same for all, the difference fell on the windage. This varied, assuming gun and projectile to be accurate, from about 0·125 to 0·250, so that it may easily be conceived the diversity of the tables of fire for this calibre of gun were very great. And although from the simple nature of the guns, and the absence of anything like mechanical contrivance connected with them, it was quite unnecessary to give to them the care and attention that are absolutely indispensable in guns of the present day, it must not be supposed that they were altogether free from liability to accident and other defects.

I had occasion recently to look into the question of the guns employed in the siege of Sebastopol, and found that in that great siege no less than 317 iron ordnance were used by this country. At the close of the siege it was found that eight had burst, one hundred and one had been condemned as unserviceable, while fifty-nine were destroyed by the enemy's fire.

The 95-cwt. 68-pr. gun seems to have been about the largest gun that could safely be made of cast iron, and that in it the limit of safety was nearly reached, was shown by the fact that a serious percentage of this calibre burst or otherwise failed. With the spherical shot the column of metal per unit of area to be put in motion by the charge was small, and to this the guns probably owed their safety.

When the same charge was used, and cylinders representing double, treble, or quadruple the normal weight of the shot were fired, the end was rapidly reached, the guns frequently bursting before cylinders four or five times the weight of the shot were employed.

But the fact that a stronger and more reliable material than cast iron was necessary, was shortly to be emphasised in a much more striking manner. The great superiority of rifled to smooth-bored ordnance in every respect, in power, in range, in accuracy, in destructive effect, of shrapnel and common shell, was in this country demonstrated by Lord Armstrong and others. This led to numerous attempts to utilise cast iron for rifle ordnance. The whole of these efforts resulted in failure. Although the charges were feebler than with smooth-bored guns, these experimental guns burst one after the other with alarming rapidity, generally before many rounds had been fired. The matter was not made much better when the expedient was adopted of strengthening these guns by hoops or rings shrunk on externally. Failures with this arrangement were little less frequent, the cast iron bursting under the jackets, and the only plans in which cast iron was used with any success were those proposed respectively by Sir W. Palliser and Mr Parsons, who inserted, the one a coiled wrought iron, and the other a steel tube in a cast-iron gun block.

But the country that suffered most severely from the use of cast iron was the United States. Their great civil war took place just when efforts were being made in every country to introduce rifled artillery. Naturally every nerve was strained to manufacture these guns, and naturally the resources that came most readily to hand were first employed.

A report presented by the Joint Committee on Ordnance to the United States Senate in 1869 gives the history of these guns, which were nearly all either cast iron, or cast iron reinforced with hoops in the way I have described. I have heard the existence of internal strains disputed, but in this report we read that ten guns burst, that is, flew to pieces, when lying on chocks, without ever having had a shot fired from them, and ninety-eight others cracked or became ruptured under like conditions.

In the "Summary of Burst Guns" in the same report, it is stated that one hundred and forty-seven burst and twenty-one were condemned as unserviceable; twenty-nine of them being smooth-bore and one hundred and thirty-nine rifled ordnance. But perhaps

the most striking passage is that which relates that in the action before Fort Fisher *all* the Parrott guns in the fleet burst, and that by the bursting of five of these guns during the first bombardment, forty-five men were killed and wounded, while only eleven men were killed or wounded by the enemy's fire.

The muzzle velocity given by the smooth-bored cast-iron guns may be taken approximately at 1600 feet per second, and at the maximum elevation with which they were generally fired their range was about 3000 yards. The 32-pr., with a charge of one-third the weight of the shot and an elevation of 10°, gave nearly 2800 yards, and the 68-pr., with a charge of about one-fourth, nearly 3000 yards. The same gun, with an eccentric shot and an elevation of 24°, gave a maximum range of 6500 yards.

But it must not be supposed because the range tables gave 3000 yards as practically the extreme range of the ordnance of thirty-five years ago, that our guns possessed any high efficiency at that distance. At short distances, from 300 to 500 yards, dependent on the calibre, the smooth-bored guns were reasonably accurate; but the errors multiplied with the distance in so rapidly increasing a ratio, that long before a range of 3000 yards was attained, the chance of hitting an object became extremely small.

It is desirable to give some idea of the accuracy, or rather want of accuracy, of these guns.

In 1858 I was appointed secretary to the first Committee on Rifled Cannon, and as the early experiments showed how extraordinary was the accuracy of the new weapons, it became a matter of importance to devise some means of comparing in this respect the old and the new guns.

The plan I proposed was one which has since in principle been followed by the artillerists of nearly all countries. It was to calculate the probable error in range and the probable error in deflection, and from these data the area within which it would be an even chance that any given shot would strike; or, in other words, that area within which, out of a large number of rounds, half that number would fall. This area was for the smooth-bored gun at a range of 1000 yards, 147·2 yards long by 9·1 yards broad, or 1339·5 square yards, while the similar area for the rifled gun at the same range was 23·1 yards long by 0·8 yards broad, or an area of 18·5 square yards. But the great decrease of accuracy due to an increase of range with the smooth-bore guns is especially remarkable. Experiments showed that with the smooth-bored gun an increase of range of only 350

yards more than doubled the error in deflection, and made the area selected for comparison 206 yards long by 20·2 broad, or 4161 square yards; as nearly as possible trebling the area for an increase in range of 35 per cent.

But I have not done yet. These experiments were made with the same lots of powder carefully mixed, and the irregularities in velocity would be such as are due to manufacturers' errors only. But the variations in the energy developed by the gunpowder employed have still to be considered. In 1860, being then an associate member of the Ordnance Committee, I carried on for the Government the first electro-ballistic experiments made in this country. My attention was early called to the great variation in energy developed by powders recently made and professedly of the same make, and I pointed out that in my experiments the variations between one lot of powder and another amounted occasionally to 25 per cent. of the total energy developed. It is unnecessary to say that on service, and when powder had been subjected to climatic influences, the variations would have been much greater.

The variations in energy of new powder were chiefly due to the method of proof then in use, the Eprouvette mortar, than which nothing can be conceived better adapted for passing into the service powders unsuitable for the guns of that time.

But with the want of accuracy of the gun itself, and the want of uniformity in the propelling agent, it may easily be conceived that a limit was soon reached beyond which it was mere waste of ammunition to fire at an object even of considerable size, and we can appreciate the reasons which led our naval commanders, whenever possible, to close with their enemy.

When we come to consider guns of the present day, the first point that attracts our attention is the enormous increase in the size and weight of the larger natures. It may fairly be asked indeed if, weight for weight, the modern guns are so much more powerful than the old, and, if we have command of such great ranges, why such heavy guns should be necessary.

The answer to this, of course, is that it has been considered essential to have guns capable of piercing at short distances the thickest armour which any ship can carry, and this demand has led us from guns of 5 tons weight up to guns of 110 and 120 tons weight, and to the development of the important mechanical arrangements for working them, to which I shall presently refer.

On the principles which guide the construction of these large

guns I shall say little, both because the subject is too technical to be dealt with in an address, and because the practice of all nations, though differing in many points of detail, in essentials is closely accordant.

On three points of construction we lay particular stress in this country. These points are:—That the gun shall be strong enough to resist the normal working pressure, even if the inner tube or barrel be completely split. That whether we regard the gun as a whole, or the parts of which it is composed, the changes of form should be as little abrupt as possible, and that any sharp angle or corner must be absolutely avoided.

As in principles of construction, so in material employed, is the practice of the great gun-making nations closely agreed. The steel employed is ductile and subjected to severe specifications and tests which differ slightly one from the other, but exact, in effect, qualities of steel substantially the same. So far as I know, the application of the tests in this country is more severe than in any other, and I take this opportunity of entering my protest against the statement which I have seen more than once in the journals of the day—that English gun-steel is in any way inferior to any that is produced in any part of the world. Sheffield has in no respect lost its ancient reputation in the art of steel-making, and to my certain knowledge has supplied large quantities of steel, admitted to be of the first quality, to gunmakers of the Continent. The steel made by Sir J. Whitworth & Co. has likewise long been in great repute both at home and abroad, and looking at the care devoted to the subject by the Government, and the eagerness with which improvements in the quality and mode of manufacture are sought for and acted on by the steelmakers, we may be absolutely certain that to the best of our knowledge the most suitable material is used in the construction of our guns.

As many of you are aware, the mild steel which is used for the manufacture of guns is after forging and rough-boring subjected to the process of oil-hardening, being subsequently annealed, by which process it is intended that any detrimental internal strain should be removed. This process of oil-hardening, introduced first by Lord Armstrong in the case of barrels, is now almost universally adopted for all gun forgings. Of late, however, there has been considerable discussion as to whether or not this oil-hardening is necessary or desirable; and while admitting the increase of the elastic limit due to the process, it is asked whether the same results would not be

obtained by taking a steel with, for example, a higher percentage of carbon, and which should give the same elastic limit and the same ductility. The advocates of oil-hardening urge that steel with low carbon, duly oil-hardened to obtain the elastic limit and strength desired, is more reliable than steel in which the same results are reached by the addition of carbon. Those who maintain the opposite view point to the uncertainty of obtaining uniform results by oil-hardening, to the possibility of internal strains, and to the costly plant and delay in manufacture necessary in carrying it out. The question raised is undoubtedly one of great importance, but it appears to me to be one concerning which it is quite within our power in a comparatively short time, by properly arranged experiments, to arrive at a definite conclusion.

In selecting steel for gun-making, individually I should prefer that which is on the side of the low limit to that which is near the high limit, of the breaking weight prescribed by our own and other Governments. I have this preference because, so far, experience has taught us that these lower steels are safer and more reliable than the stronger—and in guns we do not subject, and have no business to subject, the steel to stresses in any way approaching that which would produce fracture.

Of course if our metallurgists should give us a steel or other metal which with the same good qualities possesses also greater strength, such a material would by preference be employed, but it must not be supposed that the introduction of such new material would enable us, to any great extent, to reduce the weight of our guns. As a matter of fact, the energy of recoil of many of our guns is so high that it is undesirable in any case materially to reduce their weight. As an illustration I may mention, that some time ago in re-arming an armour-clad, the firm with which I am connected was asked if by using the ribbon construction it would be possible, while retaining the same energy in the projectile, to reduce the weight of the main armament by 3 tons per gun. The reduction *per se* was quite feasible, but when the designs came to be worked out it was found that, on account of the higher energy of recoil, no less than 4 tons weight per gun had to be added to strengthen the mounting, the deck, and the port pivot fastenings.

The chamber pressures with which our guns are worked do not generally exceed 17 tons per square inch, or, say, 2500 atmospheres. It must not be supposed that there is any difficulty in making guns to stand very much higher initial tensions, but little would be gained

by so doing. Not only can a higher effect be obtained from a given weight of gun if the initial pressure be kept within moderate limits, but with high pressures the erosion (which increases very rapidly with the pressure) would destroy the bores in a very few rounds.

In fact, even with the pressures I have named, the very high charges now employed in our large guns (1060 lbs. have frequently been fired in a single charge), and the relatively long time during which the high temperature and pressure of explosion are maintained, have aggravated to a very serious extent the rapid wear of the bores. In these guns, if the highest charge be used, erosion, which no skill in construction can obviate, soon renders repair or re-lining necessary. Reduced charges, of course, allow a materially prolonged life of the bore, and there is also a very great difference in erosive effect between powders of different composition, but giving rise in a gun to the same pressures. Unfortunately, the powder which has up to the present been found most suitable for large guns is also one of the most erosive, and powder-makers have not (so far) succeeded in giving us a powder at once suitable for artillery purposes and possessing the non-eroding quality so greatly to be desired.

An *amide* powder made by the Chilworth Company, with which I have, not long ago, experimented, both gave admirable ballistic results, and at the same time its erosive effect was very much less than that of any other with which I am acquainted. It is by no means certain that the powder would stand the tests which alone would justify its admission into the service; but the question of erosion is a very serious one, and has hardly, I think, received the attention its importance demands. No investigation should be neglected which affords any prospect of minimising this great evil.

On the introduction of rifled artillery, the muzzle velocities, which you will remember had been with smooth-bore guns and round shot about 1600 feet per second, were, with the elongated projectiles of the rifled gun, reduced to about 1200 feet per second. In the battle between plates and guns these velocities were with armour-piercing projectiles gradually increased to about 1400 feet per second, and at about this figure they remained until the appointment by the Government of a Committee on Explosives. By the experiments and investigations of this Committee it was shown that, by improved forms of gunpowder and other devices, velocities of 1600 feet per second could be obtained without increasing the maximum pressure, and without unduly straining the existing guns.

Similar advances in velocity were nearly simultaneously made abroad, but in 1877 my firm, acting on independent researches on the action of gunpowder made by myself in conjunction with Sir F. Abel, constructed 6-inch and 8-inch guns which advanced the velocities from 1600 to 2100 feet per second, and this great advance was everywhere followed by a reconstruction of rifled artillery.

With the present powder the velocities of the powerful armour-piercing guns, firing projectiles considerably increased in weight, may be taken at from 2000 to 2100 feet per second. The distance of 3000 yards, which I said practically represented the extreme range of smooth-bored guns, is attained with an elevation of only 2° in the case of the 68-ton gun, and of 3½° in the 4·7-inch quick-firing gun, while at 10° the ranges are 9800 and 5900 yards respectively, and, as an instance of extreme range, I may mention that with a 9·2-inch gun a distance of over thirteen miles has actually been reached.

Nor is the accuracy less remarkable. Bearing in mind the mode of comparison which I have already explained, at 3000 yards range the 68-ton gun would put half its shot within a plot of ground 7·2 yards long by 0·3 broad, and the 4·7-inch gun within a plot 19 yards long by 1·3 broad; or, to put it in another form, would put half their rounds in vertical targets respectively 0·92 yard broad by 0·34 yard high, and 1·3 yards broad by 1·6 yards high.

But it cannot be assumed that we are at the end of progress. Already, with the amide powder we have obtained nearly 2500 feet per second in a 6-inch gun with moderate chamber pressures, and with the cordite originated by the Committee on Explosives, of which Sir F. Abel is president, considerably better results have been obtained. I have elsewhere pointed out that one of the causes which has made gunpowder so successful an agent for the purposes of the artillerist is that it is a mixture, not a definite chemical combination; that it is not possible to detonate it; that it is free, or nearly so, from that intense rapidity of action and waves of violent pressure which are so marked with nitro-glycerine and other kindred explosives.

We are as yet hardly able to say that cordite in very large charges is free from this tendency to detonation, but I think I may say that up to the 6-inch gun we are tolerably safe; at least, so far, I have been unable, even with charges of fulminate of mercury, to produce detonation. I need not remind you that cordite is smokeless, and that smokeless powder is almost an essential for quick-firing guns, the larger natures of which are day by day rising in importance.

I now come to the third part of my subject—the modes which are now adopted of mounting and working the ordnance I have described. I have alluded to the carriages, which, at the beginning of the century, were made of wood, and were worked solely by handspikes. Thirty-five years ago they were but little changed, although in the case of pivot-guns screws for giving elevation, and blocks and tackle for training had been introduced, but timber was still the material employed. A strong prejudice long existed in both services against iron for gun-carriages, as it was believed that iron carriages would be more difficult to repair, and that the effect on the crew of splinters would be much more serious.

But when the experiment of firing at both natures was made at Shoeburyness, with dummies to represent the crews, it was found both that the wooden carriage was far more easily disabled than the wrought iron, and that the splinters from the wooden carriages were far more destructive.

In all other respects, the superiority of wrought iron as regards unchangeability, durability, and strength, was so apparent, that iron, and later steel, rapidly displaced wood. No gun-carriages, not even field, are now made of that material. It is impossible, within moderate limits, to give even a sketch of the various forms of mountings that have, as the science of artillery has progressed, been designed to meet the constantly changing conditions of warfare. I shall confine myself to the description of certain types of carriages, dividing these generally into three classes, viz., those for guns of the largest class, which require power to work them; those for guns of medium size, in which, by special arrangements, power is dispensed with; and those for guns of a smaller class, which are particularly arranged for extremely rapid fire.

With respect to the first class. On the adoption of heavily-armed, revolving turrets of the Cowper-Coles type, in which the guns are trained for direction by revolving the turret, the first idea which naturally presented itself was to utilise steam power for this heavy work. It was, however, soon recognised that, on account of its elasticity, steam did not give the necessary steadiness and control of movement essential for accuracy of aim, and water under pressure was employed as the means of transmitting the power from the steam-engine to the machinery for rotating the turret and working the guns.

On land, where an accumulator can be employed, a small steam-engine kept constantly at work is used; but at sea, where accumula-

tors, whether made to act by the pressure of steam, air, or springs, are inadmissible, a very much larger engine is employed, sufficiently powerful to supply water to perform all the operations ever carried on together. When little or no work is required, the engine automatically reduces its speed till it merely creeps, so that little or no power is consumed.

The mode of mounting the guns differs somewhat according as they are intended to be placed in a barbette or in a turret. Our guns have gradually been increasing in length, and are now so long (our largest has a length of nearly 45 feet) that it is impossible to provide an armoured turret of sufficient size to protect the forward part of the gun, and under these circumstances it is a grave question whether it is worth while to devote so much armour to the protection of what is after all the strongest part of the gun.

Of the eight new battle-ships now building, seven are to have their guns mounted *en barbette*, and one is to be provided with armoured turrets. In either case, the guns and their machinery are carried on revolving turntables of practically the same form. These turntables are placed in an armoured redoubt, and the guns, when horizontal, are entirely above the armour, but in the case of the ship provided with turrets the breech ends of the guns are covered in, with the turrets placed as an addition on the turntables.

The extra weight required thus to protect the breech ends of the guns is for this ship about 550 tons.

As the hydraulic machinery for these new ships differs but slightly from that fitted on ships of the *Rodney* and *Nile* classes, the same description will cover all these vessels. The armoured barbette battery at each end of the ship is made of a pear shape, as seen in plan, in order to provide for a pair of ammunition hoists and hydraulic rammers at its narrower end.

These ammunition hoists come right up into the armoured barbette and descend to the shell-room and magazine decks, forming the channel by which the projectiles and charges are rapidly supplied to the guns; and it must be remembered that the weight to be lifted for a single round, including powder and projectile, with the necessary cases, considerably exceeds a ton. The cage in each hoist is worked by hydraulic cylinders with double wire-ropes, and in case of breakage, automatic safety gear is fitted to arrest and lock the cage.

While on the ammunition deck the cages are charged simultaneously from either side, and when hoisted to the battery-deck are

automatically slowed, and then stopped at the proper position for loading the guns. Much depends upon the service of ammunition by these hoists being protected from interruption, and in the event of derangement of the cage, independent tackle, worked by an hydraulic capstan, is provided to take its place, and a few rounds can also be stowed within the battery.

In intimate connection with the ammunition hoists are the hydraulic rammers on the ammunition deck for charging the cages, and in the battery for loading the guns. To reduce their length within reasonable limits they are made telescopic, and they are fitted with indicators to show when the charges are home.

In the shell-rooms hydraulic cranes and traversing bogies are fitted to convey the shell to the base of the ammunition hoist, so that a projectile is transported from the place where it is stowed to the shot-chamber of the gun without manual labour of any sort except that of moving the various levers to set the hydraulic machinery in motion. In the magazines hydraulic bollards are provided for hoisting and transporting the powder-cases by means of overhead runners. Hand-gear is provided as an alternative in both magazine and shell-rooms.

Each turntable carrying the guns and their fittings is rotated by a pair of entirely independent three-cylindered engines, each engine being of sufficient power to rotate the turntable at the speed of one revolution per minute. The gear for controlling them is worked from two or three look-out stations, at either or any of which the officer has to his hand the means of elevating, training, sighting, and firing either one or both guns. The turning-engines are fitted with a powerful spring brake, which will hold in a seaway, but which is taken off automatically when the water is admitted to start the engines. Easy control is obtained by the use of servo-motor valves, so that the handwheel is small, and requires but little power to move it. It only remains to describe as shortly as possible the system of mounting the guns on the turntable. The guns are trunnionless, to allow them to be as close together as possible, with the view of reducing to the smallest possible size the diameter of the turntables. The carriages are cradles of steel grooved to correspond with rings turned on the guns, and with straps by which the guns are secured to the cradles. The carriages are mounted without rollers or wheels on slides formed of steel beams of great strength, pivoted at their front ends, and supported on hydraulic presses, by which they are bodily raised or lowered to give the guns elevation or depression.

In the case of the turret this system gives the smallest possible port. The loading of the gun is effected while the gun is at extreme elevation, a position which is easily determined by dropping the slide on to fixed stops, and which gives the best protection for the breech mechanism, for the hoist and rammers. The operations of unlocking the breech-block, withdrawing it, traversing it, inserting a loading tray, and, after completing the loading, performing the same operations in reverse order, are all done by hydraulic power, and the fittings are so devised that unless the gun is properly locked and run out it cannot be fired.

In certain foreign vessels provided with the hydraulic breech mechanism, a valve has been arranged which makes in their proper order, and in that order only, the eight or ten movements necessary to open and close the breech of the gun, but this system has not been adopted in our own navy.

The sights are carried on the top of the turntable, or, in the case of a turret, on the turret roof, and are worked automatically by an arc attached to the gun slide, gearing into cog-wheels, with shafting reaching to each sighting position.

The system of recoil press adopted on all these ships is that which lends itself most readily to employment also as a running-in-and-out press. It consists of a simple cylinder carried in the middle of the slide, having working in it a ram with piston, attached at the front end to the carriage. Spring-loaded valves are placed in the recoil ram piston and at the end of the cylinder, and by these the water escapes when the gun recoils. The water which passes through the cylinder valves runs to the exhaust-pipe, while that which passes through the piston valve remains in the front of the cylinder, and prevents the gun charging out again. When the recoil press is used to run the gun in and out these valves are inoperative, as they are loaded much above the working pressure in the hydraulic mains. The high pressure of recoil does not enter the hydraulic mains, as the supply to the rear of the press, where alone the high pressure of recoil exists, is made backwards and forwards, through a valve which shuts itself automatically when not in use.

Before leaving the working by power of heavy guns, there is one example of mounting a pair of guns *en barbette* which, although it has many points in common with the system I have just described, has also some points of difference, which it may be worth while to note

Objections have sometimes been urged to the fixed loading station on the ground that it is necessary to bring the guns to it

and lock them there until sponged and loaded, thereby involving, not only a loss of time, but under certain conditions exposing them more to the enemy's fire.

In ships of the *Re Umberto* type, what is termed an all-round loading is obtained by bringing up the ammunition through a central hoist to the deck below the turntable. From this central hoist it is transferred to two other hoists, which are carried on the turntable behind the guns. The transfer is made by hand for the powder and by sliding down a tray for the projectile, this work being performed by men on the deck below the turntable. The hydraulic rammers are fixed to the turntable, and are very much shortened by being made with more rams. In spite of this arrangement, however, the hoists are rather cramped, and the breech mechanism has to be made to pass from behind the gun, so as to permit the gun to recoil, and the gun is rather further forward than usual when run out.

With these reservations, however, the system has advantages: the reduction in the armour required to protect the turntable and its machinery is considerable, and the redoubt being round instead of pear-shaped presents a smaller and stronger surface to the enemy when broadside on.

I very much doubt, however, whether with this system there can be any advantage in rapidity of fire. Training to the loading station is in our navy very quickly done, and the turntable is rotated while the guns are being run in or out.

It is hardly necessary to say that hydraulic machinery for guns was worked out by my friend and late partner Mr George Rendel, and up to the end of 1881 all details connected therewith were made under his management.

I ought perhaps to give you some idea of the rate at which these heavy guns worked by power can be fired.

In the case of the *Benbow*, with the 110-ton gun the time from "load" to "ready" was 2½ minutes. In the firing trials of the *Trafalgar* four rounds were fired from one of her 68-ton guns in 9 minutes 5 seconds. In the *Colossus*, when under command of Captain Cyprian Bridge, the average from one round to another was 1 minute 45 seconds, and on one occasion, steaming at 8 knots per hour past a target at a distance of 1500 yards, she fired four rounds in 6 minutes, striking the target three times.

Of the mountings which are worked solely by manual power, the whole range for naval service is covered by the carriages of the type designed by Mr Vavasseur. No single description can be made to

cover all the varieties of these mountings, which have been worked out to meet the diverse conditions which have arisen in the re-arming of old ships, and the fitting out of new vessels on modern and novel designs. The very general adoption of breech-loading ordnance brought with it the necessity for a mounting which would give easier access to the breech of the gun than was obtained with the long low gun-slide employed with the muzzle-loading guns. The main features of the type therefore are, a high slide, very short, so as not to project beyond the breech of the gun, a short low carriage carrying on either side the recoil-presses, and a shield to afford protection both to the carriage and the gun crew.

The increased importance of rapid-fire guns has led in later carriages to a strong armour plate being built into the mounting as part of its structure, and to this must be added the shield above-mentioned, so that the total protective thickness of plate is very considerable.

By means of a worm-wheel sliding on a keyed shaft, the movement of the gun for elevation or depression can be made up to the instant of firing—a decided and very important advance on the older methods.

The arrangement of the recoil-cylinders is peculiar. They are fitted with a pair of pistons with rotating valves, so adjusted as to be open when the gun is in the firing position, and to be gradually closed during recoil by studs running along rifled grooves in the cylinders; by this ingenious contrivance the area of the ports of the valves is increased and then decreased in proportion to the variation of the velocity of recoil, so that the liquid passes from one side of the piston to the other at as nearly as possible a constant velocity and under a constant pressure. The velocity of the flow through the ports, and therefore the pressure of the liquid, varies with the energy of the recoil of the gun, so that the length of the recoil is with all charges practically the same.

Even a blank charge produces nearly full recoil, and on one occasion caused one of these mountings to be reported as unserviceable, and unfit to fire a shotted round. Constant length of recoil has the advantage over constant pressure in the recoil-presses that, in the event of an unusually heavy recoil, a higher pressure in the recoil-press would in the former case be the only result, and would do no harm, as the pressure would still be much below the test-pressure; but in the latter case there would be an increased length of recoil, and, unless considerable margin were allowed, a possible destruction of the slide.

Most frequently the Vavasseur mountings are made with central

pivots, and there is then little tendency for the movements of the vessel to affect the mounting, and as the weight is borne upon a ring of live rollers the greatest ease of training is obtained.

In the larger sizes the centre pivot is increased in size, and made hollow so as to provide for the passage through the centres of a powder hoist, which, after rising high enough, curves to the rear under the gun and delivers its charge at the point where it can most conveniently be drawn out for insertion in the gun. In this case a foot-plate is also provided as a rear attachment to the slide, and from this the crew work the gun. This foot-plate is provided with boxes for eight or ten projectiles, which are therefore ready for use at any moment and in any position of training. These mountings are fitted in the belted cruisers of the *Orlando* class, one being carried at the fore and one at the after end of each ship.

As a sufficient proof of the value of these mountings and of the ability which had been displayed in their design, I may mention that practically all countries have adopted these carriages for modern guns, either without any alteration or with comparatively unimportant modification.

In discussing our modern ordnance I only alluded to quick-firing guns, because in their case the gun and mounting are so closely connected, the efficiency of the system depending as much upon the one as the other, that a separate description of either would be incomplete, and they are more easily described together. The great success which attended the small Hotchkiss and Nordenfelt 3- and 6-pr. guns led me to consider whether the same principle could not be applied to large guns, and we designed and made at Elswick the 4·7-inch and 5·5-inch quick-firing guns which were so successfully tried by the *Excellent* at Portsmouth. Subsequently, with the co-operation of Mr Vavasseur, various improvements were made, and for the sake of uniformity in calibre a 6-inch was substituted for the 5·5-inch gun.

One of the peculiarities of these guns is in the form of the breech-screw, which, while on the principle of the interrupted screw, is made conical so as to simplify the action of opening and closing—the principle of the ordinary rifle cartridge has been extended to the ammunition of these guns. This not only allows extremely rapid loading, but secures safety from premature explosions in rapid firing. The cartridges are fired electrically, and, not having their own ignition, there is no danger of exploding them either when stowed in the magazine or if accidentally dropped in the handling.

To follow the rapid movements of a torpedo boat it is essential that there should be the most perfect control over the gun and mounting, and the most effective mode of rapid fire is to keep the gun always on the object aimed at, allowing the gun itself to fire as the breech is closed. The captain stands at the side of the gun, shielded by a guard-plate from the recoil, his shoulders braced against a shoulder-piece which is unaffected by the recoil; his eye aligns the sights; with one hand he works the elevating or training wheel, and with the other grasps the firing-trigger, or, for rapid firing, the training-wheel may be thrown out of gear, and direction given by the shoulder-piece alone. The mounting is a centre pivot, and, being on live rollers, turns with the least effort. The gun has no trunnions, but slides in a carriage which envelops it like a sleeve. The trunnions are on this carriage, so that the two are together pivoted like an ordinary gun in a fixed lower carriage. There is no preponderance when the gun is in the forward position, and the recoil lasts for so short a time that the disturbance of the centre of gravity is not felt on the elevating-gear or shoulder-piece. The lower side of the carriage is formed into a recoil-press, the piston-rod of which is attached to a horn on the rear of the gun.

There is also a spring-box, with rod attachments to the horn, by which the gun is instantly run out as soon as the recoil is expended. Efficient shields are provided to protect the crew. The revolving weight of the gun and mounting is 5 tons, yet with the shoulder against the shoulder-piece, it can be swung through 90° in 2 seconds, and with the gear can be trained through the same arc in 5 seconds. It is possible to fire from this gun at the rate of 10 to 12 rounds per minute, and on one occasion 10 rounds were fired in 47 seconds; but perhaps the most striking experiment with the gun was made at Shoeburyness, when 5 rounds were fired in 31 seconds at a $6' \times 6'$ target at 1300 yards, all of which struck the object aimed at.

A trial has also been recently made between two cruisers, the one armed with ordinary breech-loading, the other with quick-firing artillery, from which it appears that when firing at a target, the latter, in a given time, was able to discharge about six times the quantity of ammunition fired by the former. I need not impress upon you the significance of these facts or the importance of quick-firing armaments, especially if firing shell, possibly charged with high explosives, against the unarmoured portions of cruisers or other vessels.

The accuracy and the shell power of rifled guns have naturally

had their effect upon the mountings for the land service, experiments having conclusively shown that batteries armed with guns placed in ordinary embrasures would soon be rendered untenable. Among the expedients that have been adopted or suggested to meet the altered conditions, the system of making the gun disappear behind a parapet or into a pit, with which the name of Colonel Moncrieff has been so long and so honourably associated, is more and more coming into favour, as the most effective mode of protection for the gun and its mounting, as well as for the gun detachment. During the last ten years much attention has been devoted to the designing of various mountings on this system for all weights of guns from 3 up to 68 tons.

In the earliest carriages of this type the gun was raised by the descent of a balance weight, but the most successful arrangement is that in which compressed air is employed for the purpose. The 9·2-inch and 10-inch hydro-pneumatic mountings are the largest sizes as yet adopted into the English service, and a description of them will serve for that of the type generally.

The gun on this system is raised by compressed air stored in several chambers, and acting through the medium of a fluid upon a recoil ram.

On the recoil of the gun the liquid is driven from the cylinder by the incoming ram into the lower parts of the air chambers, so that as much as is required of the energy of recoil is stored up by the compression of the air, and is used to raise the gun for the next round. The gun is raised up and lowered on two heavy beams pivoted to the lower carriage. Two long, light elevating rods, pivoted at one end to the breech of the gun, at the other to the lower carriage, hold the gun in correct position as it rises or falls; the elevation is changed by moving the position of the lower ends of the elevating rods. This can be done when the gun is down without disturbing it, and consequently with very little labour. The effect of the change is apparent after the gun rises, when any slight correction can be made if desired. Generally these mountings have been made with overhead shields placed a little below the level of the top of the gun pit, and entirely closing it. There is an aperture through which the gun rises, but which can be closed when the gun is out of action.

In the case of the 10-inch gun the total weight of the revolving mass is 80 tons. Only two men are required at the hand-wheels to revolve it—in fact, it is within the power of *one* man to do the whole

work. The ordinary speed of training is 90° in $1\frac{1}{4}$ minute, while the time required to raise the gun to the firing position is 20 seconds. The speed of rising might be considerably increased, but, taking the weight of the mass in motion into account, it does not appear to be desirable to accelerate it.

At Maralunga, Spezia, in March of the present year, the first 68-ton disappearing mounting, manufactured for the Italian Government, was tried with most satisfactory results. Fifteen rounds were fired in all, some of them being made to give greatly increased energy of recoil, with the view of proving the gun and mounting.

The gun was worked entirely by hand-power, and on land no difficulty is experienced in thus dealing with it, while the system possesses the advantage that it is always ready for use should it be required, but no great alteration is necessary to adapt the mounting for use with hydraulic power.

In this case the water from the recoil-press is driven through spring-loaded valves instead of into air chambers. There is, therefore, no storing up of the recoil energy, and to raise the gun to the firing position, water pressure from an accumulator kept charged by a steam pumping-engine in the usual way is employed. These guns and mountings are too large to be easily covered by an overhead shield, but they are provided with shields at the front and rear to protect the gun detachments.

Another very successful mounting for land service has been made for guns when the site is such that it is permissible to place them *en barbette*. The gun is entirely above the parapet, but the detachment is protected while loading and working the gun by a broad sloping shield carried on the gun-carriage and recoiling with it. The shield is inclined so that any splinters, etc., striking it may be deflected in an upward direction.

The carriage runs back on a long slide inclined at 5°, and at the end of the recoil is caught by a spring catch, which retains it in the run in position until the loading is finished. To load, the gun is put at extreme elevation, so that the breech may be as much under protection as possible, the charge being rammed home with a hand rammer worked by rope tackle. The slide is mounted on front and rear rollers, and has an actual centre pivot. The recoil is controlled by a single Vavasseur recoil-cylinder placed in the centre of the slide, and giving a constant length of recoil for all charges, so that the spring catch to retain the gun at extreme recoil for loading is always reached.

To run out after loading, the spring catch is released, and the incline of the slide is sufficient to cause the gun to run out, which it does smartly, but is checked and brought to rest quietly by means of a controlling ram placed at the end of the recoil-press.

But I must conclude. I trust I have said enough to satisfy you as to the indebtedness of the naval and military services to mechanicians and to mechanical science, but you will also understand that within the limits of an address it is impossible to give a complete survey of so large a subject, and that there are important fields I have left wholly untouched.

IX.

NOTE ON THE ENERGY ABSORBED BY FRICTION IN THE BORES OF RIFLED GUNS

(*Proceedings of the Royal Society*, 1891.)

The object of the experiments which I proceed to describe was to ascertain approximately, and under varied conditions, the loss of energy due to the friction of the driving-ring of the projectile in the bores of rifled guns.

The rotation of modern breech-loading projectiles is generally given by means of a copper ring or band on the projectile, on a plan originally proposed by Mr Vavasseur, the diameter of this ring being not only somewhat larger than that of the bore, but even larger than the diameter of the circle representing the bottom of the grooves, and the projections which give the rotation are formed by the pressure of the powder-gases forcing the driving-ring into the grooves of the gun. At the commencement of motion the driving-ring is consequently exactly moulded to the section of the bore at the seat of the shot, and under the conditions due to the pressure to which the gun is at the moment subjected.

It will readily be conceived that a band or ring, moulded as described, may give rise to considerable friction in its passage through the bore, and the amount of this friction may be modified to a considerable extent by various circumstances.

For example, the nature of the powder employed may, depending on the deposit or fouling left in the bore, affect appreciably the friction. Again, the friction may be considerably modified by the form and diameter of the ring itself, while a variable amount of energy must be absorbed by the methods employed to give rotation, and by the amount of that rotation.

In the preliminary experiments three descriptions of powder were employed—(1) the powder known as P., or the pebble-powder of the

English Service; (2) an amide powder in which the nitrate of potassa of ordinary powder is largely replaced by nitrate of ammonia, and which powder, in addition to other valuable properties, gives rise to a smoke much less dense and much more rapidly dispersed than is the case with pebble and other similar powders; and (3) a true smokeless powder. The form of smokeless powder employed in this country is best known under the name of *cordite*, a propelling agent which promises to be of great value, and for which we are indebted to the labours and experiments of Sir F. Abel and Professor Dewar. A somewhat similar explosive is employed abroad under the name of "ballistite," and with this explosive also I have been able to make an interesting series of experiments. These experiments do not, however, come within the scope of the present note.

The preliminary experiments having shown that a very considerable amount of friction was, in the case of pebble-powder, due to the fouling of the gun, while no such result was observed either in the case of the amide powder or the cordite, it was determined to carry out the subsequent experiments with the amide powder, firing, however, for purposes of corroboration an occasional round with the cordite, of which a small quantity only was available.

It may be of interest to note the loss of velocity and energy due to the fouling with pebble-powder. The charge of powder in a 12-cm. gun being 12 lbs., and the weight of the shot 45 lbs., the velocity of the shot, the gun being carefully cleaned and oiled, was, in three trials, respectively, 1877 feet per second, 1877 feet per second, and 1878 feet per second. The two rounds fired immediately afterwards, the bore then being foul, were respectively 1850 and 1868 feet per second, 1848 and 1847 feet per second, 1852 and 1847 feet per second; or, taking the means of the whole series, the mean velocity with the gun clean was 1877·3 feet per second, with the bore foul, 1852 feet per second; or, to put the result in another form, the mean energy realised from the pebble-powder, the bore being carefully cleaned, and allowance being made for the energy of rotation, was 1102 foot-tons, while the mean energy similarly realised with the bore foul was only 1072 foot-tons; showing a loss of 30 foot-tons or of 2·73 per cent. of energy attributable to the extra friction due to the powder deposit in the bore.

For the purposes of the subsequent experiments, three 12-cm. quick-firing guns were specially prepared and rifled in the following manner:—The first had grooves of the usual section of the service, but these grooves were all cut parallel to the axis of the bore, that is

to say, the pitch of the rifling was infinite, or, in other words, there was no twist, and no rotation round the central axis would be communicated to the projectile; the second gun was rifled with a uniform pitch of 1 turn in 162 inches (about 1 turn in 35 calibres); while the third gun was rifled with a uniformly-increasing pitch of from 1 turn in 472″·5 at the breech to 1 turn in 162″ at the muzzle, so that in the last two guns, assuming the same muzzle velocity, the projectiles would leave the gun with the same angular velocity.

The projectiles used in these experiments were flat-headed cylinders (all being made of the exact weight of 45 lbs.), and differed from one another solely in the driving-bands of the projectiles, which differed from one another both in diameter and length, the differences being shown in the sketches attached to the tabular results.

The first experiments were made with the rings marked "A" (fig. 1), three rounds being fired from each of the three guns described, and the following table shows the velocities and energies obtained from each nature of gun.

Section "A."

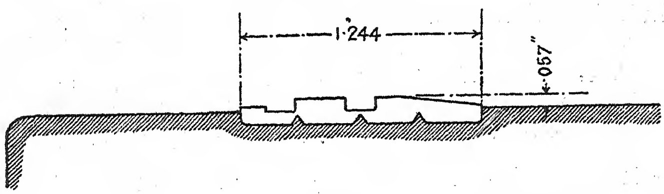


Fig. 1.

Table 1.—*Results of experiments with driving-rings. Section "A."*

Nature of rifling.	Muzzle velocities.	Muzzle energies.	Mean muzzle velocity.	Mean muzzle energy.
	F. S.	F. T.	F. S.	F. T.
No twist . . .	2130 2124 2136	1416 1408 1424	2130	1416
Uniform rifling . .	2109 2104 2118	1394 1386 1405	2110	1395
Parabolic rifling .	2079 2088 2076	1354 1365 1350	2081	1356

Now, if the results given in this table be examined, it will be observed that the whole of the velocities obtained from the gun with-

out twist are higher than those obtained from the gun rifled with a uniform twist, while the whole of the velocities obtained from the last-mentioned gun are higher than those obtained from the gun with the parabolic or uniformly-increasing twist.

Using the mean results, there is a loss of velocity of 20 feet per second in passing from the gun with no twist to that with a uniform twist, and a further loss of 29 feet per second, or 49 feet per second in all, in passing to the gun with the parabolic rifling. Translating these losses of velocity into losses of energy, it appears that there is a loss of 21 foot-tons, or about 1·5 per cent. of the total energy due to the uniform rifling, and a further loss of 39 foot-tons, or 2·75 per cent., making 60 foot-tons, or about $4\frac{1}{4}$ per cent. in all, when the parabolic rifling is emoloyed.

In a paper published in vol. xlv. of the *Philosophical Magazine* (1873) I investigated the ratio existing between the forces tending to produce translation and rotation in the bores of rifled guns, and I showed that, if R be the pressure tending to produce rotation, and G be the gaseous pressure acting on the base of the projectile, the resultant of which pressure acts along the axis of the bore, that is along the axis of Z, then in the case of the parabolic rifling

$$\mathrm{R} = \frac{2\rho^2(\mathrm{G}z + \mathrm{M}v^2)}{\dfrac{(h^2k^2 + 4\rho^2z^2)\sin\delta}{\sqrt{\{4z^2(\sin\delta)^2 + k^2\}}} + \dfrac{2\mu_1 kz(\rho^2 - h^2)}{\sqrt{(4z^2 + k^2)}}} \quad . \quad . \quad (1)$$

where r is the radius of the bore, ρ the radius of gyration of the projectile, k the principal parameter of the parabola (the plane of xy being supposed to be at the vertex of the parabola and at right angles to the axis of the bore), δ the angle which the normal to the driving-surface of the groove makes with the radius at the point under consideration, v the velocity at that point, μ_1 the coefficient of friction.

While in the case of a uniform twist

$$\mathrm{R} = \frac{2\pi\rho^2\mathrm{G}}{\dfrac{\mu_1(2\pi\rho^2k - rh)}{\sqrt{(1+k^2)}} + \dfrac{(2\pi\rho^2 + rhk)\sin\delta}{\sqrt{\{k^2 + (\sin\delta)^2\}}}} \quad . \quad . \quad (2)$$

where h is the pitch of the rifling, k the tangent of the angle which the groove makes with the plane of xy, the other constants, etc., bearing the meaning I have already assigned to them.

Now to obtain the numerical values of R from the above equations, a knowledge of the values of G, that is, of the total pressures acting

on the base of the projectile, and in the case of the parabolic rifling of the velocity at all points of the bore, is necessary, and, the

TABLE 2.—*Uniform rifling, amide powder.*

Travel of shot in bore, in feet.	Total pressure, etc., on base of shot, in tons.	Total pressure R between driving surface of grooves and ring of projectiles, in tons.
0·5	254·7	19·9
1·0	264·0	20·7
1·5	245·0	19·2
2·0	207·9	16·3
2·5	175·7	13·7
3·0	150·7	11·8
4·0	115·2	9·1
5·0	94·9	7·4
6·0	80·6	6·3
7·0	69·5	5·4
8·0	60·0	4·7
9·0	52·1	4·1
10·0	44·8	3·5
11·0	38·4	3·0
12·0	32·9	2·6
13·0	28·4	2·2
14·0	24·3	1·9
14·4	22·6	1·8

TABLE 3.—*Parabolic rifling, amide powder.*

Travel of shot in bore, in feet.	Total pressure on base of shot, in tons.	Velocity, feet per second.	Total pressure R between driving surface of groove and ring of projectile, in tons.
0·5	254·7	548	7·9
1·0	264·0	849	9·7
1·5	245·0	1064	10·3
2·0	207·9	1224	10·5
2·5	175·7	1343	10·5
3·0	150·7	1437	10·4
4·0	115·2	1577	10·5
5·0	94·9	1680	10·8
6·0	80·6	1761	11·1
7·0	69·5	1828	11·4
8·0	60·0	1884	11·6
9·0	52·1	1931	11·8
10·0	44·8	1970	11·9
11·0	38·4	2004	12·0
12·0	32·9	2032	12·0
13·0	28·4	2056	12·1
14·0	24·3	2076	12·1
14·4	22·6	2084	12·1

explosives used being novel, for this investigation, as well as for other purposes, I have recently determined by direct experiments in

the bore of a 12-cm. quick-firing gun the mean velocities and mean gaseous pressures at all points of the bore, both for the amide powder, mainly used in this investigation, and for cordite.

The curve shown on Plate XXI. (p. 396) exhibits for the charges used and explosives I have named the results of these experiments, and, employing these values, the tables on p. 389 give for uniform and parabolic rifling the value of R, that is, the pressure tending to give rotation calculated from formulæ (1) and (2). They also give the pressure acting on the base of the shot, and the velocity in the bore.

The values of R, as given in the last columns of the above tables, are graphically shown on Plate XXII. (p. 396), and from a comparison of the two curves it will be readily seen that, although the maximum pressure between the driving-surfaces is not so high with the parabolic as with the uniform rifling, yet, as has been pointed out by Professor Osborne Reynolds, the mean driving-pressure is with the parabolic rifling considerably higher, and as the energy absorbed by the friction between the driving-surfaces is approximately proportional to the mean driving-pressures, the loss of energy with that form of rifling is appreciably greater than with the uniform rifling.

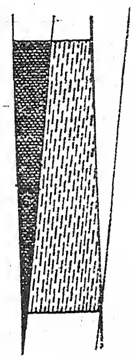
In the experiments I am now discussing the mean driving-pressure throughout the bore was, with the uniform rifling, 7·35 tons; the mean loss of energy due to the uniform rifling was 21 foot-tons; hence the coefficient of the friction between the driving-surfaces derived from these particular experiments is $\mu = 0{\cdot}199$.

Again, with the parabolic rifling, the mean driving-pressure throughout the bore is 11·06 tons, and if we had only a similar friction to consider, the loss of energy with this rifling should be proportioned to the pressure. The loss, however, is much higher, amounting, in fact, to 60 foot-tons. Part of this extra loss must be ascribed to the continual alteration of form that the copper driving-ring is subjected to in its passage up the bore,* but it seems to be doubtful if the whole of this loss can be ascribed to this cause. Part may possibly be ascribed to the ribs being continually forced, so to speak, to ride

* The action I refer to will readily be understood from the annexed diagram (fig. 2). If the thick lines represent the plan of one of the grooves at the initial angle of the rifling, the projections on the driving-ring will be moulded into that form, and if the light lines represent the groove at its terminal angle, it will be seen that the final form of the projections on the ring will be as shown by the shading, while the cross-hatched portion represents the metal removed by the action of the driving-surface.

on to the sloping-driving-surface; but the number of rounds in each case being few, a part may possibly be ascribed to variations in the energy devoloped in the gun. Variations in energy, under precisely similar conditions, might easily amount to 1 or 2 per cent., or occasionally more, and, as will be subsequently seen, the differences between the uniform and parabolic rifling, although always in the same direction, are not the same in all the series, and the mean of the whole will probably give the most reliable result.

FIG. 2.



Summing up the results at which we have so far arrived in the experiments I have discussed, it appears that the total loss of energy arising from the fouling of pebble-powder and from the friction due to the parabolic rifling together, amounted to close upon 7 per cent. of the whole energy developed.

The third and subsequent series of experiments were made some weeks later, and from climatic or other causes there was a slight but decided decrement in the energy obtained with the amide powder. This decrement did not in any way affect the experiments, except that the absolute values of the energies at the different dates are not strictly comparable.

The object of the third series was to ascertain if a narrow driving-band would rotate the projectile equally well, as with an increasing twist it is important, if rotation be secured, that the breadth of the driving-band be as small as is convenient, and further, as in the last series, to ascertain the loss of energy due to the uniform and parabolic rifling.

The results of this third series were as shown in Table 4 (p. 392).

The results of this series confirm generally those of the previous series. The loss of energy due to the friction of the uniform rifling amounts to 14 foot-tons, or a little more than 1 per cent., while that due to friction and other causes with the parabolic rifling amounts to 57 foot-tons, or about 4·1 per cent., and nearly the same as before. The difference between the uniform and parabolic rifling should have been less than in the former series; as a matter of fact it is greater, but this may be accounted for by variations in the powder as previously suggested, as the suppression of a single round in each of the two guns would make the results in accordance with theory.

Section "B."

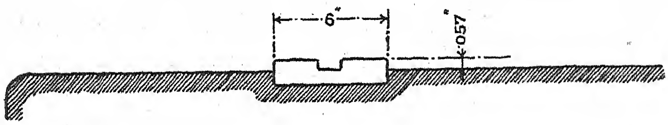


FIG. 4.

TABLE 4.—*Results of experiments with rings of section "B."*

Nature of rifling.	Muzzle velocity.	Muzzle energies.	Mean muzzle velocities.	Mean muzzle energies.
	F. S.	F. T.	F. S.	F. T.
No twist	2112 2104 2124	1392 1381 1408	2113	1394
Uniform twist	2109 2094 2095	1393 1373 1375	2099	1380
Parabolic twist	2067 2066 2066	1338 1337 1337	2066	1337

Section "C."

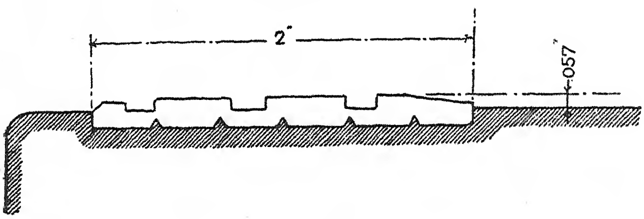


FIG. 5.

TABLE 5.—*Results of experiments with driving-rings of section "C."*

Nature of rifling.	Muzzle velocities.	Muzzle energies.	Mean muzzle velocities.	Mean muzzle energies.
	F. S.	F. T.	F. S.	F. T.
No twist	2131 2114 2114	1417 1394 1394	2120	1402
Uniform twist	2092 2082 2088	1371 1358 1365	2087	1364
Parabolic rifling	2068 2066 2071	1339 1337 1343	2068	1340

The coefficient of friction calculated from the uniform rifling gives $\mu_1 = 0{\cdot}133$.

The driving-ring in this series was amply sufficient for rotative purposes, there not being even with the highest velocity obtained the slightest appearance of slip or undue wear.

In the fourth series the driving-ring was of the government pattern, but longer, and as is shown in section "C," and the results obtained were as given in Table 5.

The loss of velocity due to the uniform and parabolic rifling is, from these experiments, respectively 33 and 52 feet per second, and the loss of energy respectively 38 and 62 foot-tons, or, expressed in percentages, 2·71 per cent. for the uniform rifling and 4·72 per cent. (the highest reached) for the parabolic rifling.

The value of μ_1, the coefficient of friction, calculated from the uniform rifling, is 0·359.

The fifth and sixth series were fired with driving-bands of the government pattern, but with radii successively slightly increased, as shown in the diagrams, and the results are given in Tables 6 and 7 (p. 394).

From these two tables it will be seen that the loss of velocity due to the uniform and parabolic rifling is, in Table 6, 12 feet per second and 64 feet per second respectively; and in Table 7, 18 feet per second and 36 feet per second respectively; these velocities corresponding to losses of energy of 12 foot-tons and 19 foot-tons due to the uniform twist, and 41 foot-tons and 42 foot-tons, or about 3 per cent., due to the parabolic rifling. Calculated as before from the uniform rifling, the coefficients of friction are respectively 0·114 and 0·208.

Examining now with respect to the uniform rifling the whole of the series I have described, and observing that with this rifling the particular form or width of the driving-ring would have but a very slight, if any, effect upon the loss of energy due to friction, it will be seen, from Table 8, that the mean loss of energy amounts to 1·52 per cent. of the total energy, corresponding to a mean coefficient of friction of 0·203, or, say, 0·2.

If, as I have pointed out, the loss of energy in the parabolic rifling was proportional to the pressure on the driving-surfaces, the additional loss due to that rifling would be 0·74 per cent. The actual additional loss is, on the mean of the whole of the experiments, about three times as great, the mean loss due to parabolic rifling being, as shown by Table 8 (p. 395), 3·78 per cent., and

Section "E."

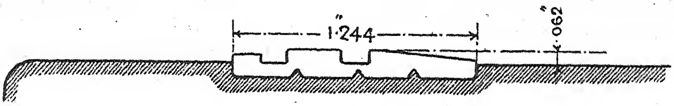


Fig. 6.

Table 6.—*Results of experiments with driving-rings of section "E."*

Nature of rifling.	Muzzle velocities.	Muzzle energies.	Mean muzzle velocities.	Mean muzzle energies.
	F. S.	F. T.	F. S.	F. T.
No twist . . .	2132 2124 2123	1418 1408 1406	2126	1411
Uniform rifling . .	2113 2115 2114	1398 1401 1399	2114	1399
Parabolic rifling .	2099 2095 2081	1380 1375 1356	2092	1370

Section "F."

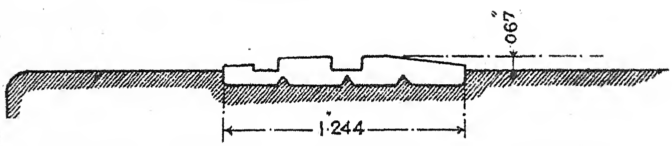


Fig. 7.

Table 7.—*Result of experiment with driving-rings of section "F."*

Nature of rifling.	Muzzle velocities.	Muzzle energies.	Mean muzzle velocity.	Mean muzzle energy.
	F. S.	F. T.	F. S.	F. T.
No twist . . .	2112 2141 2141	1392 1430 1430	2131	1417
Uniform rifling . .	2104 2110 2124	1378 1384 1413	2113	1398
Parabolic rifling .	2093 2099 2094	1372 1380 1373	2095	1375

this considerable increment may be ascribed to the causes I have mentioned.

TABLE 8.—*Showing the percentage of loss of energy due to friction in the various series; showing also the deduced value of the coefficient of friction.*

Series.	Loss due to uniform rifling.	Loss due to parabolic rifling.	Coefficient of friction.
	Per cent.	Per cent.	μ_1
2	1·48	4·23	0·199
3	1·01	4·09	0·133
4	2·71	4·72	0·359
5	0·85	2·90	0·114
6	1·55	2·97	0·208
Means .	1·52	3·78	0·203

It may be worth while to mention that, in the groove formerly used in the service, the angle between the normal to the driving surface and the radius could, without serious error, be taken as $=90°$. In the groove adopted in the guns under consideration the mean value of δ is only about 34° 45′, and this difference in the driving-angle increases the value of R, and, in consequence, the friction, by about 76 per cent. It would be interesting to make careful experiments to ascertain if there be any measurable difference in energy if an angle more nearly approaching to 90° were adopted. On account of the different length of the radius of gyration in the case of a solid shot and of a shell, the value of R is considerably affected when the latter projectile is fired. The difference of values is shown by the curves on Plate XXII.

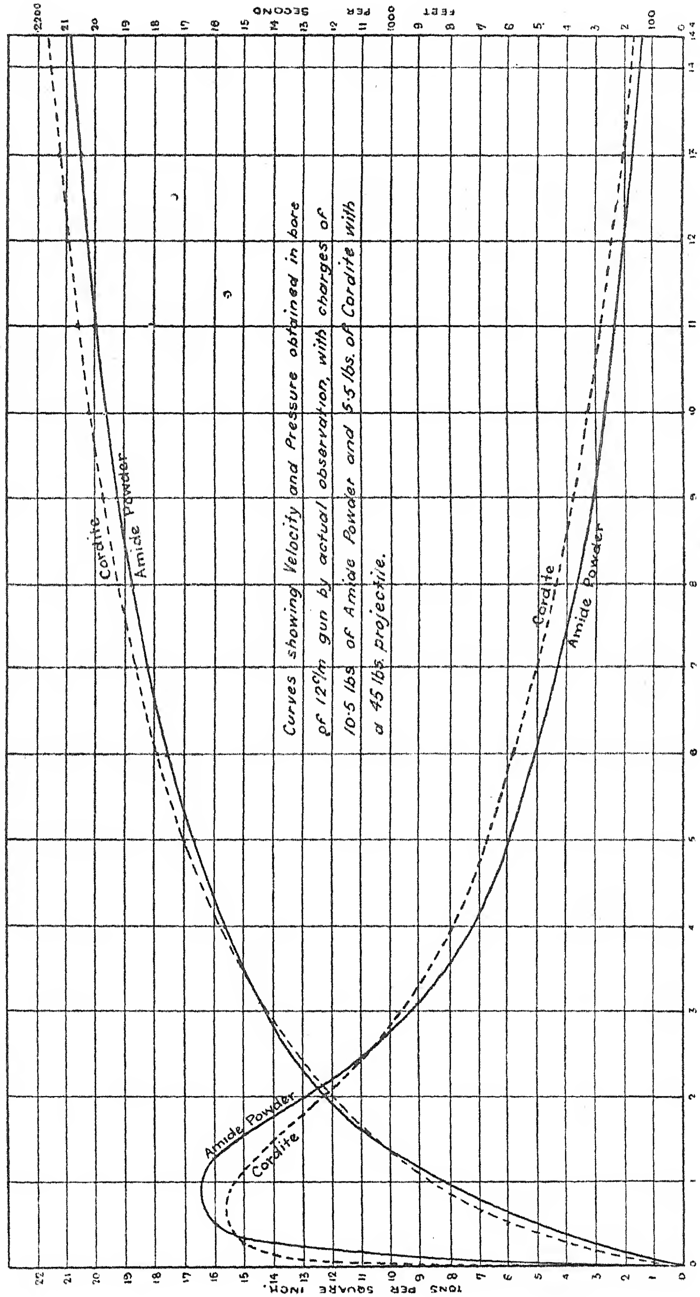
In nearly all the countries of Europe an increasing twist is the form of rifling usually adopted; and, with such a consensus of practice, it must be assumed that some advantage is supposed to be gained by its use. There is, of course, with the parabolic rifling a less maximum pressure on the driving-surfaces; but, as far as energy is concerned, both theory and the experiments I have detailed concur in showing that there is a distinct and very appreciable loss resulting from its employment. It is quite possible, although I am not acquainted with any carefully-conducted experiments on the point, that superior accuracy may be the advantage obtained; and if this were decidedly so, a loss of one or two per cent. of energy would not be, perhaps, a serious price to pay; but as, without any inconvenience, the question of accuracy could be easily settled, I trust that before very long this point also may be definitely determined.

It only remains to give the results obtained with cordite. At the time the experiments were made, I had only at my disposal a very limited amount of this explosive, and I was only able to fire one round in each of the guns, using the driving-rings marked A, B, and C. As it would be useless to attempt to draw general conclusions from single rounds, and as in guns of the calibre experimented with the difference between the driving-rings is not very marked, I have treated the series as if all the rounds had been fired with the same driving-ring; the results are given in Table 9.

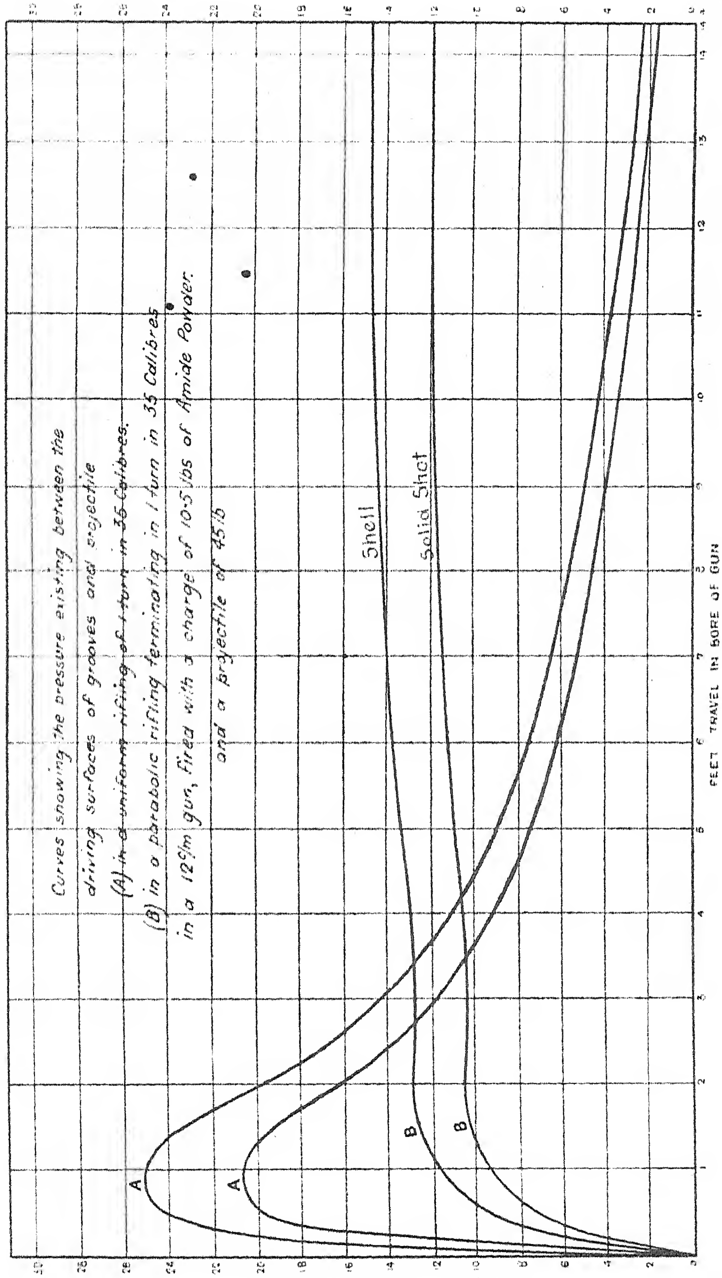
TABLE 9.—*Results of experiments with cordite.*

Nature of rifling.	Muzzle velocities.	Muzzle energies.	Mean muzzle velocities.	Mean muzzle energies.
	F. S.	F. T.	F. S.	F. T.
No twist . . .	2177 2171 2194	1479 1476 1509	2181	1488
Uniform rifling . .	2160 2161 2172	1461 1462 1477	2164	1467
Parabolic rifling .	2156 2152 2157	1455 1450 1457	2155	1454

From the cordite experiments, it follows that the loss of energy due to the uniform rifling is 21 foot-tons, or 1·43 per cent., and to the parabolic rifling 34 foot-tons, or 2·3 per cent.: the coefficient of friction deduced from the loss of energy with the uniform rifling being 0·199, or nearly the same value as was given in Table 8.


Curves showing Velocity and Pressure obtained in bore of 12c/m gun by actual observation, with charges of 10·5 lbs of Amide Powder and 5·5 lbs. of Cordite with a 45 lbs. projectile.
Cordite
Amide Powder
FEET TRAVEL IN BORE OF GUN
TONS PER SQUARE INCH
FEET PER SECOND

[To face p. 396.


Curves showing the pressure existing between the
driving surfaces of grooves and projectile
(A) in a uniform rifling of 1 turn in 35 Calibres.
(B) in a parabolic rifling terminating in 1 turn in 35 Calibres
in a 12c/m gun, fired with a charge of 10·5 lbs of Amide Powder
and a projectile of 45 lb
Shell
Solid Shot
A
A
B
B
FEET TRAVEL IN BORE OF GUN
TOTAL PRESSURE IN TONS

X.

INTERNAL BALLISTICS

(*Lecture delivered before the Greenock Philosophical Society,* 12*th February* 1892, *in honour of the anniversary of the birth of James Watt.*)

In the lecture I am about to deliver, some account will be given of the progress that has been made in the science of artillery during my own lifetime; but that progress without the work of Watt, and the manufacturing facilities he has placed at our disposal, would have been impossible. In treating of artillery, I shall have to occupy myself to a large extent with the explosive substances which are, or may be, used as propelling agents. I shall in certain instances exhibit the decomposition that explosives undergo, and endeavour to show that in the realisation of their explosive power, heat, a mode or form of motion, plays the whole *rôle;* and in the application of explosives to artillery, that a gun may be considered as one of the simplest forms of a thermo-dynamic machine—the bore may be taken as resembling the cylinder of a steam engine, while the projectile may be considered as the accurately fitting piston. The pressures developed are, it is true, enormously higher than in the steam engine; but by means I shall describe, diagrams of these pressures at all points of the bore can be made, and will be exhibited to you.

The explosives that are probably best known to most of you are those in which certain chemical compounds or mixtures are converted instantaneously, or at least in an extremely minute space of time, into a gaseous or partially gaseous mass, occupying a volume very many times greater than that of the original body; such decomposition being generally associated with an immense development of heat, the heat of course exercising a most important influence, not only on the pressure developed, but on the energy which the explosive is capable of generating.

Gunpowder, guncotton, amide powder, picrates of potassa and ammonia, nitro-glycerine, fulminates, and among the new explosives, ballistite and cordite may be cited as explosives of this class; examples of the majority of these explosives are on the table

before you, and it is with this class that artillerists have chiefly to deal.

But I need hardly say that there are numerous classes of explosives, of a very different character from the class I have cited above. In that class which consists generally of a substance capable of burning, and of a substance capable of supporting combustion, both descriptions of substances are in the solid state. In, for instance, gunpowder or cordite, the carbon is associated with the oxygen in an extremely condensed form; but prior to the reaction, the oxidisable and oxidising substances may be either, as in the class I have cited, solid, or they may be liquid or gaseous, or any combination of these three states of matter. Some examples of such explosives will readily occur to you.

Again, finely divided substances capable of oxidation may, when mixed with atmospheric air, form explosives which have occasionally been very disastrous, while the minute particles of coal-dust floating in the atmosphere of our mines have either originated serious and fatal explosions, or in a very high degree intensified the disastrous effects of an explosion of marsh-gas.

Flour dust and sulphur dust suspended in the air, have also occasionally given rise to serious explosions; while, as instances of the explosive effects of a mixture of gases I need only cite those of mixtures of air or oxygen with carbonic oxide, of marsh-gas with oxygen, or of the mixture of hydrogen and oxygen forming water, which, if regard be had to the weight of the combining substances, forms an explosive possessing a far higher energy than is possessed by any other substance with which I am acquainted.

In the course of my lecture, I propose in the first instance to select one or two of the simpler cases of explosives, with the view of drawing your attention to some important points, but shall devote my main attention to gunpowder, at once the best known, and in its decomposition the most complicated, of the explosives with which we have to deal.

I have stated that an explosive may be either solid, liquid, or gaseous, or any combination of these three states of matter. As my first illustration, I will take an explosive in the gaseous form, and one which I have more than once cited as being the simplest form of explosive we can select.

If we take equal volumes of hydrogen and chlorine at a temperature of 0° Cent. and a barometric pressure of 760 mm., mix them, and apply a light, the mixture will explode violently, and hydrochloric

acid will be formed by the explosion. If we suppose the gases to be fired in an indefinitely long tube, closed at one end, and with an accurately-fitting piston working in it, the piston, immediately the gases are fired, will occupy a very different position on account of the great expansion due to the heat produced by the combination; but if we suppose the gases to be cooled so that the whole apparatus is again reduced to the temperature and barometric pressure from which we started, the piston will be found to have returned to its original position, the combined gases occupying precisely the same space as they did prior to the explosion.

Now this particular case of an explosive is of great importance to us, because, as you will have noted, the exploded gases at the same temperature occupy precisely the same space as before, and the explosion is not complicated by any absorption or increment of heat due to change of state of the explosive, or by any condensation or reduction in volume.

One of the most important points connected with the theory of any explosive, is the determination of the quantity of heat generated when a given charge is fired. By the expression "quantity of heat" you of course understand that I do not refer in any way to the temperature of the fired explosive, a point which I shall also discuss, but to its thermal capacity, or power of communicating heat to some standard substance. Quantities of heat are usually expressed in units of weight of water heated by a fixed amount (generally 1°) on some thermometric scale. In England the unit frequently is a pound of water raised through 1° Fahr. Thus 1 lb. of carbon in burning to carbonic acid is said to be capable of generating 14,500 British units of heat, that is, to be capable of raising 14,500 lbs. of water through 1° Fahr. English chemists, however, now almost invariably adopt the French unit, and the unit I shall use will be 1 grm. of water raised through 1° Cent.

The heat caused by the explosive I am now considering amounts to about 23,000 grm.-units per gramme of hydrogen, or to about 600 grm.-units per gramme of the mixed gases, and these figures express, without addition or deduction, the energy or total amount of work stored up in the unexploded mixture; and from that datum, knowing the specific heat, we are able to calculate not only the work which the gases, in expanding under the influence of the heat generated, are capable of performing, but also approximately the temperature of explosion, and the maximum pressure produced by the explosion.

If, instead of a volume of chlorine and a volume of hydrogen, we

take two volumes of hydrogen and one volume of oxygen, these being the proportions which when combined form water, there is much greater development of heat than in the case of hydrogen and chlorine.

The explosion is not quite so simple. You will remember that with the chlorine mixture, when the exploded gases were again reduced to the temperature and pressure existing before the explosion, the piston, which was supposed to be free to move in an indefinitely long cylinder, returned to its original position. In the present case, however, the piston will be found to stand, not at the original height but at two-thirds of that height, so that the aqueous vapour has suffered a condensation of from three volumes to two volumes, and the great heat indicated by the calorimeter (about 3300 grm.-units) per gramme of the mixed gases is an index of the energy stored up in the unexploded gases. From this determination we are able, as in the last instance, to determine approximately the temperature of explosion, and the pressure exerted on the walls of a close vessel at the moment of explosion.

You will remember I have stated that, with reference to weight, the potential energy of this mixture of hydrogen and oxygen is higher than that of any other known substance; but various difficulties which will readily occur to you have prevented its use either as a disruptive or propelling agent.

I now turn to explosives which before their explosion are in the solid state, and I shall select those which are principally used as propelling or disruptive agents.

Commencing with gunpowder—the oldest and the best known explosive—it is easy to see how the name arose; but the term is a complete misnomer when applied to some of the samples I have here, and which may be new to some of you.

Here is the powder known as "R. F. G.," *i.e.*, rifled fine grain. It differs very slightly in appearance from ordinary sporting powder. Here is "R. L. G.," or rifled large grain. Here pebble. Here a so-called powder known as P_2. I exhibit a single grain, and you will note to what a formidable size it has attained. Here is ordinary prismatic powder, and here again a prismatic powder about which I shall have something to say, known as brown prismatic, or cocoa-powder. Here is amide prismatic—a powder in which a portion of the nitre of ordinary powder is replaced by nitrate of ammonia.

I propose, in my remarks, to draw your attention chiefly to investigations and researches on the phonomena attending the

explosion of gunpowder which have been carried on during recent years, and with which I have been more or less connected; and I shall not refer to the labours of earlier investigators except when it may be necessary to point out in what respect the conclusions I draw differ from those of the eminent men who have laboured in the same path, and when I do so differ, I shall endeavour to give you, as clearly and concisely as I can, the grounds upon which my own conclusions are based.

And I shall first address myself to the examination of what occurs when a charge of powder is fired in a vessel in which the products of combustion are absolutely confined. If we suppose a charge to be so fired, there are a number of questions which have to be answered before we are in a position to theorise as to what happens in our close vessel, or in the more important case of a charge fired in a gun.

Among such questions, and to which in the course of my remarks I shall endeavour to give answers, are the following:—

(1) What is the metamorphosis experienced by gunpowder in its explosion? or, in other words, what substances are produced by its combustion?

(2) What proportions of the products of combustion are at ordinary temperatures non-gaseous?

(3) What proportion are permanent gases? and what is the volume of these permanent gases?

(4) In what state do the non-gaseous products exist at the moment of explosion?

(5) What is the quantity, that is, what is the number of units of heat produced by the combustion of a given weight of gunpowder?

(6) What is the temperature of the products of combustion at the moment of explosion?

(7) What are the mean specific heats of the products of explosion?

(8) What is the relation between the tension of the products of explosion and their mean density?

(9) What changes, if any, are produced in the products of explosion by varying the gravimetric* densities of the charge?

(10) What is the effect of changes in the chemical composition of

* The gravimetric density of a charge in the chamber of a gun or explosion-vessel is the ratio between the weight of the charge and the weight of water at its standard density which would fill the chamber.—Thus, if the chamber of a gun would hold 100 lbs. water, and the gun be fired with a charge of 80 lbs., the gravimetric density of the charge is ·8.

powder on the products of explosion, on their tension, or on the heat developed?

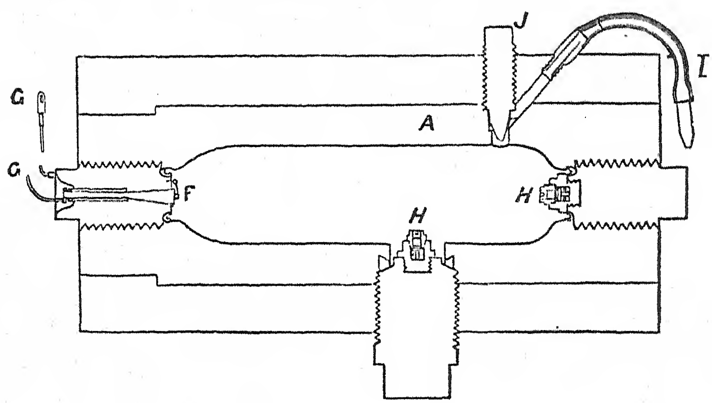
(11) What alteration, if any, is produced on the same variables by changes in the physical characteristic of the powder, such as, for example, changes in the density and size of grain, presence of moisture, etc.?

Now, in attempting to answer these questions, and others which may arise in the course of my remarks, I shall, in this first part of my subject, describe chiefly experiments that have been carried on by myself in conjunction with my distinguished friend Sir F. Abel.

But before passing to the results of our researches I propose to give you a description of the vessels in which the explosions were produced, and two forms of this apparatus are exhibited in Figs. I.

Fig. I.

EXPLOSION VESSEL.



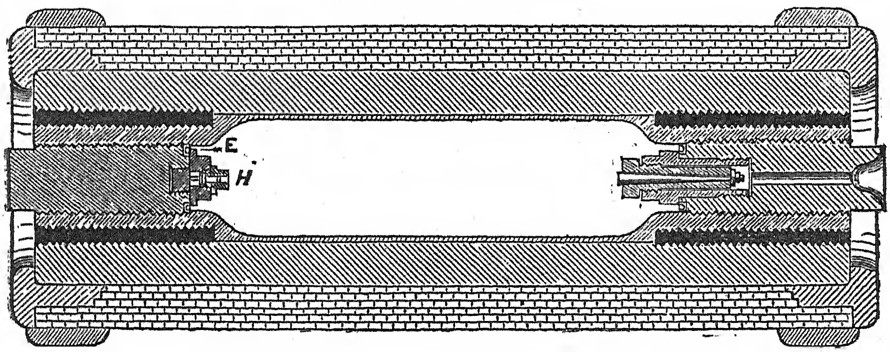
and II. The first vessel was employed for moderate charges, and for experiments connected with measurement or analysis of the gases. The vessel in Fig. II. is intended for the combustion of very large charges.

The vessel in Fig. I. consists of a steel barrel A, open at both ends, the two open ends being closed by carefully-fitted screw plugs furnished with the gas-checks E, Fig. II., to prevent any escape past the screw. The action of the gas-check is not difficult to understand. The pressure acting on both sides of the annular space E presses these sides firmly against the cylinder and against the plug, and should there be no failure of the parts, effectually prevents any escape. In the firing plug is a conical hole closed by the cone F, which is ground into its place with great exactness, and which, when

the cylinder is prepared for firing, is covered with very fine tissue paper to act as an insulator. The two wires, G, G, one in the insulated cone, the other in the firing plug, are connected by a very fine platinum wire passing through a glass tube filled with mealed powder. This wire becomes red-hot when connection is made with a Leclanché battery, and the charge is thus fired. It is hardly necessary to say that, after firing, the cone is firmly pressed into its place, and the only effect of pressure is the more completely to close the aperture. To illustrate how completely and thoroughly this cone does its work, I may say that when the cylinder has been subjected to a very heavy pressure frequently, no amount of hammering will loosen it or indicate that it does not form part of the firing plug itself. To remove it, it is necessary to heat the whole plug to a red

FIG. II.

EXPLOSION VESSEL.



heat, and when the tissue paper is destroyed the cone comes away easily. The crusher-plug is fitted with a crusher-gauge H for determining the pressure of the gases at the moment of explosion, and in addition to this gauge I have frequently had one or two gauges (later on I will draw your attention to these) placed loose in the interior of the cylinder. I is the passage for letting the gases escape. When it is wished to do this, the screw J is slightly withdrawn. When the gases pass into the passage I, they can be led to suitable vessels where their volume can be measured, or portions of them may be sealed for analysis by methods that have been elsewhere fully described.

Before leaving the explosion apparatus, one or two interesting points may be noted. If, as generally happened, the vessel was perfectly tight, there was on firing no sound whatever, or if high

charges of powder were used, a slight "click," caused by the trifling motion of the cone forced by the pressure more firmly into its seat.

The sound in this respect offered a strong contrast to that caused by guncotton, the motion of the cone in this case, though only through two or three thousandths of an inch, producing an exceedingly sharp sound like that of a percussion cap or the snapping of a strong musket-lock. But if any of the screws were not perfectly home so that no appreciable amount of gas could escape, the gases instantly on their generation cut a way for themselves, and the sound in this case varied according to the rapidity of escape, from a hissing sound like steam escaping at high tension, to one approaching the violence of an explosion. It may be worth while to note that in the case of a charge of powder not absolutely confined, but allowed to escape through a vent of the size ordinarily used in the guns, the gases escape with such rapidity that the report with F. G., or R. F. G., can hardly be distinguished from that of a gun.

If the diameter of the vent, however, be halved, the duration of the report is distinctly perceptible.

The effect of the escaping gases on the metal is very remarkable. I submit for your examination a cone and a gas-check past which the products of combustion have accidentally escaped, and I also submit a vent through which the products of explosion of a considerable charge have, for a special experiment of my own, been allowed to escape. You will note that the great enlargement of this vent from its original size was made by a single discharge, and you will further observe in all these instances the singular appearance of the metal at the points of escape, the metal presenting the appearance of having been washed away in a state of fusion by the rush of the highly-heated products. The examination of the effect produced by a single discharge—and that, taking into consideration the magnitude of the charges which are now used, not a large one—will enable you to appreciate how it is that guns of the present day became so severely scored after firing what would, when I entered the service, have been considered a very moderate number of rounds.

To give you an idea of the appearance of this scoring, I have here two impressions, one of part of the bore of a gun before issue, and another the impression of the same part of the bore, showing severe scoring.

I will add, that when scoring has once become marked the deterioration proceeds with ever-increasing rapidity, and under certain circumstances shows a tendency to develop cracks. To avoid what

would, in the old construction of guns, be a great danger, nearly all modern guns are so constructed as to be capable of withstanding the normal working pressures even should the inner tube or lining be entirely cracked through.

The powders which in the first place chiefly occupied the attention of Sir F. Abel and myself in our researches were those which were then used in the service for war purposes, and which were known as F. G., R. F. G., and pebble. Their composition was approximately 75 parts of saltpetre, 15 charcoal, and 10 of sulphur; but our researches have extended to a great variety of other powders, and in the annexed table, No. 1, I give an analysis, not only of the Waltham-Abbey powders, but of a variety of other powders differing considerably either in composition or in physical characteristics from Waltham-Abbey powders. With each of the Waltham-Abbey powders a very numerous series of exceedingly laborious experiments have been made. For each powder, among other experiments, the products of explosion have been collected and analysed for gravimetric densities,

TABLE 1.—*Composition of gunpowders experimented with.*

	Powder "A."	Powder "B."	Powder "C."	Powder "D."	Cocoa.	Pebble, W.A.	R.L.G., W.A.	F.G., W.A.	Spanish.	C. & H. No. 6.	Mining.
Saltpetre	·8130	·7783	·6374	·7724	·7883	·7476	·7456	·7391	·7559	·7468	·6192
Sulphur	·0018	·0028	·1469	·0615	·0204	·1007	·1009	·1002	·1242	·1037	·1506
Charcoal	·1671	·1972	·2018	·1543	·1780	·1422	·1429	·1459	·1134	·1378	·2141
Water	·0181	·0217	·0139	·0118	·0133	·0095	·0106	·0148	·0065	·0117	·0161
Units of heat	800	715	525	745	837	721·4	725·7	738·3	767·3	764·4	516·8

ascending from ·1 until the explosion-vessel was as full as it would hold; and for each of these experiments the tension of the gaseous products at the moment of explosion was determined.

I shall not fatigue you by detailing the results of the analysis of these experiments, but I have placed on the annexed table, No. 2, the mean results of the decomposition of the powders, and in the last two columns you will note that the proportions of the solid and gaseous products are given for each description of powder.

Let me now make a little experiment which I dare say most of us, at one time or other in our lives, have made for ourselves. On these plates I have trains of two or three varieties of ordinary powder. I fire them, and you will note, in the first place, that an

TABLE 2.—*Showing the decomposition of the powders in Table* 1.

Nature of Powder.	Weight of Gaseous Products.								Weight of Solid Residue.										Totals.	
	Carbonic anhydride.	Carbonic oxide.	Nitrogen.	Sulphydric acid.	Marsh-gas.	Hydrogen.	Oxygen.	Water.	Potassium carbonate.	Potassium sulphate.	Potassium hyposulphite.	Potassium monosulphide.	Potassium sulphocyanate.	Potassium nitrate.	Potassium oxide.	Ammonium sesquicarbonate.	Sulphur.	Water pre-existent.	Gaseous products.	Solid residue.
Powder "A"	·2253	·0529	·1158	...	...	·0022	...	·0225	·5474	·0017	·0048	·0034	...	...	...	·0058	...	·0181	·4187	·5812
,, "B"	·1915	·1014	·1200	...	·0019	·0042	...	·0026	·5296	·0006	·0008	·0006	...	...	...	·0240	...	·0217	·4216	·5773
,, "C"	·2723	·1315	·0875	·0191	·0056	·0011	...	...	·2036	·0042	·0073	·1646	·0187	...	...	·0081	·0627	·0139	·5171	·4831
,, "D"	·2467	·0529	·1188	·0091	·0006	·0011	...	...	·4579	·0230	·0029	·0382	·0005	...	...	·0016	·0352	·0118	·4292	·5711
Cocoa-powder . . .	·2198	·0086	·1049	...	·0004	·0006	...	·0832	·4360	·1332	...	...	...	...	...	...	...	·0133	·4175	·5825
Pebble, W.A., means .	·2685	·0477	·1123	·0111	·0006	·0006	...	...	·3258	·0710	...	·1042	·0014	·0013	...	·0005	·0445	·0095	·4409	·5582
R.L.G., W.A., means .	·2630	·0422	·1117	·0109	·0008	·0009	·0002	...	·3415	·0844	...	·0807	·0013	·0015	...	·0004	·0490	·0106	·4298	·5694
F.G., W.A., means . .	·2689	·0355	·1123	·0101	·0004	·0007	·0003	...	·2861	·1252	...	·0999	·0007	·0009	·0056	·0003	·0381	·0148	·4282	·5716
Spanish	·2457	·0136	·1108	·0096	...	·0003	·0007	...	·2186	·2975	...	·0473	·0003	·0058	...	·0002	·0431	·0065	·3808	·6193
C. & H. No. 6 . . .	·2593	·0247	·1132	·0083	·0046	·0008	...	...	·3413	·1250	...	·0717	...	·0017	...	·0005	·0372	·0117	·4109	·5891
Mining	·2279	·1522	·0858	·0389	·0070	·0017	...	...	·1945	·0028	...	·1745	·0139	·0004	...	·0084	·0664	·0161	·5135	·4770

appreciable time is taken by the flame to pass from one end to the other; but you will also note that there is a large quantity of what is called smoke slowly diffusing itself in the air.

Now this so-called smoke is really only finely-divided solid matter existing as a fluid, or volatilised only to a very slight extent at the moment of explosion; and if the powder you have just seen fired had been exploded in larger quantity in a close vessel such as I have described, nearly 60 per cent. of the weight of the powder would have been converted into the so-called smoke, and when the products had cooled would have been found at the bottom of the cylinder in the shape of a dense, hard, evil-smelling substance, generally very difficult of removal, with a smooth, dark surface, and an olive green fracture.

In the bottle which I hold in my hand, I exhibit to you a portion of the so-called smoke of a charge of 15 lbs. of powder fired in a close vessel in the manner I have mentioned.

I need hardly call your attention to the magnitude of the charge which has thus been entirely confined. At the date of the Crimean war the highest charge of the 56 cwt. 32-pr., the principal heavy gun of the service, was only 10 lbs., but I have fired and succeeded in absolutely retaining in one of these vessels a charge of no less than 23 lbs.

The principal constituents of the solid residue are potassium carbonate, potassium sulphate, and potassium sulphide, with small quantities of the other substances you see in Table 2. There are considerable fluctuations in the proportions of the principal constituents, two charges fired as nearly as possible under the same circumstances frequently differing more in the products of decomposition than do others in which both the nature of powder used and the gravimetric density at which they are fired have been changed. For these fluctuations it is difficult to assign any cause, unless it be that in a combination and decomposition of such violence, the nascent products find themselves in contact sometimes with the products of explosion, sometimes with powder not yet consumed.

But it may interest you to know the appearances presented by the solid products when cool, and after the opening of the cylinder in which the powder was exploded. The whole of the solid products were usually found collected at the bottom of the cylinder, there being but an exceedingly thin deposit on the sides. The surface of the deposit was generally quite smooth, and of a very dark grey, almost black, colour; this colour, however, was only superficial, as

through the black could be perceived what was probably the real colour of the surface, viz., a dark olive green. The surface of the deposit and the sides of the cylinder had a somewhat greasy appearance, and were, indeed, greasy to the touch. When the charge was large and the confined gases at a high pressure were allowed to escape rapidly, the surfaces, especially in the vicinity of the point of escape, were covered with a deposit of solid carbonic acid, this deposit arising from the cooling effect due to the rapid expansion.

In cases where the gas had escaped before the deposit was cold, the surface was rough, and the deposit somewhat spongy, as if occluded gas had escaped while the deposit was still in a semi-fluid state. In various experiments, on examining the fracture as exhibited by the lumps, the variation in physical appearance was very striking, there being differences in colour and texture, and also frequently a marked absence of homogeneity, patches of different colour being interspersed.

There was no appearance of general crystalline structure in the deposit, but shining crystals of sulphide of iron were frequently observed. The deposit had always a powderful odour of sulphuretted hydrogen, and frequently smelt strongly of ammonia. It was always extremely deliquescent, and small portions, after a short exposure to the air, became black, gradually passing into the inky-looking, pasty substance familiar to you all as resulting from the residue left in the bores of guns after practice.

As in physical appearance, so in behaviour, when removed from the cylinder, the solid products presented great differences. In most cases, during the short period that elapsed while the deposit was being transferred to thoroughly dry and warm bottles, no apparent change took place, but in some a great tendency to development of heat arising from the absorption of oxygen from the air was apparent. In one case where a deposit exhibited this tendency to heat in a high degree, a portion was ground, placed in the form of a cone on paper, and observed. The action proceeded very rapidly, the deposit on the apex and in the interior, where there was greatest heat, changing rapidly in colour to a light sulphury yellow, with a tinge of green.

During the development of heat, the residue gave off a good deal of vapour, and an orange-coloured deposit, probably resulting from this vapour, formed on the surface. The smell was very peculiar, sulphuretted hydrogen being distinctly perceptible, but being by no means the dominant odour.

The maximum temperature occurred at about twenty minutes after the commencement of the exposure—a thermometer placed in the centre showing a temperature of over 600° Fahr. The temperature was no doubt somewhat higher, but the thermometer had to be removed, to avoid fracture. The paper on which this deposit was placed was entirely burned through.

From an examination of the cylinder when opened after an explosion, it was easy to see that the solid products had been in a fluid state; but to ascertain the state of the contents at different periods, the following experiments were made. The cylinder, being about two-thirds full of powder, was fired, and 30 seconds after explosion was tilted so as to make an angle of 45°. Two minutes later it was restored to its first position. On opening, the deposit was found to be lying at the angle of 45°, and the edges of the deposit were perfectly sharp and well-defined.

Again, the cylinder being about three-fourths filled with powder, was fired, and allowed to rest for 1 minute after explosion. It was then placed sharply at an angle of 45°, and 45 seconds later was returned to its first position. Upon opening, it was found that when the cylinder was tilted over, the deposit had just commenced to congeal, for upon the surface there had been a thin crust, which the more fluid deposit underneath had broken through. The deposit was at an angle of 45°, but the crust through which the fluid had run was left standing like a sheet of ice.*

Another experiment with the vessel completely full of powder showed that at a minute and a minute and a quarter after explosion the non-gaseous products were still perfectly fluid, and that it was nearly 2 minutes before their mobility was destroyed; and my conclusion from the whole of the experiments is, that immediately after explosion the non-gaseous products are collected at the bottom of the vessel in a fluid state, and that some time elapses before the products assume the solid form.

The existence of this fluid residue in the bore of a gun is sometimes clearly shown by the occurrence of large splotches of residue, frequently close to the muzzle, and which indicate that considerable masses of the residue, travelling at a high velocity, had been arrested

* NOTE.—In consequence of this action, in later experiments the deposit was not removed by chisels, but distilled water, freed from air by long-continued boiling, was siphoned into the explosion-vessel, so that air was never allowed to come into contact with the solid residue—when the cylinder was thus quite filled with water, it was closed, and allowed to stand until the residue was completely dissolved.

by striking the sides of the bore. In the chambers of guns, again, considerable masses are frequently found, the residue having evidently, while in a fluid state, run down the sides and collected at the bottom of the chamber. In the 100-ton gun chamber masses of about three-quarters of an inch in thickness have been found. One of these specimens is before you.

Turn now to the gaseous products. These do not exhibit the variations shown by the solid products; on the contrary, if the powder be of similar composition, as, for instance, in the case of the Waltham-Abbey powders, the gases are remarkably uniform in composition. In weight they amount to about 43 per cent. of the unexploded powder, and consist chiefly of carbonic anhydride, nitrogen, carbonic oxide, and sulphuretted hydrogen, with small quantities of marsh-gas and hydrogen. The proportion of carbonic acid was found slightly, but decidedly, to increase as the gravimetric density of the charge was increased; this, of course, corresponding with increased pressure in the explosion-vessel, and pointing, under this condition, to a more perfect oxidation of the carbon.

The quantity of permanent gases generated by explosion differs very considerably with the nature of the powder, and even with the size of grain. Thus the quantity of gas generated by a gramme of dry pebble-powder was found to be 278·3 c.c.; by a gramme of R. L. G., 274·2; and by a gramme of F. G., 263·1. All the above volumes are reduced to the standard barometric pressure of 760 mm., and the temperature of 0° Cent.

I ought perhaps to explain, that the statement that a gramme of powder generates so many cubic centimetres is equivalent to the assertion that, at the temperature and pressure stated, the gases occupy the same number of times the volume that the powder occupied in the unexploded state, the gravimetric density of the unexploded powder being supposed to be unity.

You will observe that there is an appreciable difference in the volume of the permanent gases generated by Waltham-Abbey pebble-powder and F. G., two powders which are intended to be of precisely the same composition, and which in reality differ but slightly. But if I take some other powders I have experimented with, you will find that the differences in the volumes of the gases produced are very striking. Thus 1 grm. of Curtis & Harvey's well-known No. 6 powder generated 241 c.c., 1 grm. of English mining 360·3 c.c., while 1 grm. of Spanish pellet generated only 234·2 c.c.

Table 3 shows the volumes of permanent gases evolved by the

combustion of 1 grm. of the powders whose composition was exhibited in Table 1.

TABLE 3.—*Showing the volumes of permanent gases evolved by the combustion of 1 gramme of the undermentioned powders.*

	Powder "A."	Powder "B."	Powder "C."	Powder "D."	Cocoa.	Pebble, W.A.	R.L.G., W.A.	F.G., W.A.	Spanish.	C. & H. No. 6.	Mining.
Volumes of gases .	254	315	347	282	198	278	274	263	234	241	360

Observe, now—for I shall shortly have occasion to draw your attention to the point—the arrangement of these six last powders on the list. If I place them in ascending order of magnitude with respect to the volumes of gas they respectively generate, first we have the Spanish pellet with 234 volumes, next comes the Curtis & Harvey with 241 volumes, then F. G. with 263, and so on, while mining-powder with 360 volumes closes the list.

You will remember I have explained to you what I mean by the expression "quantity of heat." All the powders in Table 1 have, by carefully conducted calorimetric experiments, had the number of units of heat they were capable of evolving carefully determined, and the results of these determinations are given in Table 4.

TABLE 4.—*Showing the units of heat evolved by the combustion of 1 gramme of the undermentioned powders.*

	Powder "A."	Powder "B."	Powder "C."	Powder "D."	Cocoa.	Pebble, W.A.	R.L.G., W.A.	F.G., W.A.	Spanish.	C. & H. No. 6.	Mining.
Units of heat . .	800	715	525	745	837	721	726	738	767	764	517

As in the case of the quantity of gas, so with the heat evolved there is a great variation, but with this peculiarity, that the powders producing the largest quantity of gas evolve the least quantity of heat. Take, for example, the six last powders on the table to which I recently drew your attention. You will remember that when I gave you the volumes of gas generated by the different powders, I arranged the powders in an ascending order of magnitude. Now that I give you the quantities of heat evolved by the same powders,

I arrange them in descending order, and I want you to observe, as you will see from Table 5, that not only do the same powders head and close the list, but that the order of arrangement taken from the two sets of data is absolutely identical.

TABLE 5.

Nature of powder.	Units of heat per gramme exploded.	Cubic centimetres of gas per gramme exploded.
Spanish pellet	767·3	234·2
Curtis & Harvey's No. 6	764·4	241·0
W.A.F.G.	738·3	263·1
W.A.R.L.G.	725·7	274·2
W.A. pebble	721·4	278·3
Mining	516·8	360·3

Observe also, that although the mining-powder generates about 50 per cent. more gas than does the Spanish spherical, on the other hand about 50 per cent. more heat is generated by the Spanish than by the mining-powder. As a matter of fact, the products of the quantities of heat multiplied by the volumes of gas generated (which may be taken approximately as a measure of the potential energy stored up) do not differ very greatly from a constant quantity, and as a further matter of fact, the pressures developed by the powders at various gravimetric densities are very much the same, and this circumstance is remarkable when the variety in the composition of the powders and the decomposition which they experience is taken into account.

But another question here arises, and that is, are we able in any way to account for the great difference in the quantity of heat measured when two powders, such as mining and Spanish, are exploded? I believe we are, and I shall endeavour to make my meaning intelligible.

You are all aware that when, for example, ice at 0° Cent. is converted into water at 0° Cent., or when water at 100° Cent. is converted into steam at 100° Cent., a large quantity of heat has to be communicated to the ice or water as the case may be,—and as this heat produces no effect on the thermometer, it has received the name of latent heat.

But the modern theory of heat—I need not detain you with an explanation of this theory—has shown that the heat which was supposed to have become latent has really disappeared in performing work of one sort or another—in doing work against molecular forces,

or in communicating motion to the molecules of water. In placing a gramme of water at 100° Cent. in the form of steam at 100° Cent., no less than 537 units of heat are absorbed.

Again, you all probably know that when a gramme of carbon unites with a single equivalent of oxygen, the gas carbonic oxide is formed; and that when a second equivalent of oxygen is taken up, carbonic anhydride, or in the old nomenclature carbonic acid, is formed. But the quantities of heat generated when carbon burns to carbonic oxide, and when carbon or carbonic oxide burn to carbonic acid, are well known, and it appears that while the union of one gramme of carbon with an equivalent quantity of oxygen burning to carbonic oxide gives rise only to about 2445 units of heat, the assumption of the second equivalent quantity of oxygen gives rise to 5615 units, or to 8060 units in all.

Now I think we may regard it as certain that the great difference indicated in the heat shown by the figures I have given you is due to the fact, that when carbon burns to carbonic oxide a very large proportion of heat escapes measurement, because its potential energy has been expended in placing the solid carbon in a gaseous form, just as in the case of water and steam which I cited just now, a large amount of heat is absorbed in placing the steam in a gaseous form; but when carbonic oxide, which is already a gas, burns to carbonic acid no such expenditure of heat is necessary, and we are able to measure, and if need be to utilise, the whole quantity, or at all events the greater proportion of the heat generated.

You will now, I think, have no difficulty in understanding the interpretation I put upon the relation between the quantities of heat generated and the quantities of permanent gas evolved by the various powders with which I have experimented.

The case is by no means a simple one, as a glance at Tables 2 and 3 will show you how numerous are the substances which play a part in the metamorphosis, and in addition the powders themselves differ very considerably; but I venture to lay down the broad rule, that the heat measured by the calorimeter in the case of the mining-powder is greatly less than that measured in the case of the Spanish powder, because a much larger quantity of heat has been expended in placing the solid constituents of the powder in a gaseous state.

Coming now to specific heat; since we know the specific heats at ordinary temperatures of the solid products of explosion, and since we know also the specific heats of the permanent gases, we should be in a position to determine the actual temperature of explosion if

we could assume that the specific heats of the solid products remained invariable over the great range of temperature through which they pass.

Our distinguished predecessors in researches on gunpowder (Bunsen and Schischkoff) made this assumption, and from it calculated the temperature of explosion to be 3400° Cent., about 6150° Fahr. Sir F. Abel and I are, however, agreed in considering this hypothesis quite inadmissible.

I know of no exception to the general experience that the specific heat is largely increased in passing from the solid to the liquid state. The specific heat of water, for example, in so passing is doubled, and in addition it is more than probable that even with liquids the specific heat increases very considerably with the temperature.

For these reasons, I consider it certain that the temperature of explosion calculated in the manner followed by Bunsen and Schischkoff would give a temperature much higher than that really attained. But the determination of the real temperature is a matter of extreme difficulty and doubt. I employed two methods to settle the point, and these two methods gave approximately the same temperatures.

The first method I can only briefly describe, as its basis rests on theoretical considerations. It may be thus described. If we know the space in which a given quantity of permanent gases are confined, if we know also the pressure they exert upon the walls of the chamber in which they are confined, we have the necessary data for determining at what temperature the gases must be. Now the course of our researches (and to these I shall presently refer) led us to a pretty definite conclusion as to the space that the permanent gases occupied at the moment of explosion when confined in a close vessel, and a calculation from the data I have mentioned gave a temperature of nearly 2200° Cent.

To check this theoretical temperature I made numerous experiments with sheet and wire platinum of various degrees of thickness, also with similar wires of iridio-platinum. Now if the platinum, when the vessel is opened, were found completely melted, this would be a proof that the temperature of explosion is considerably higher than the melting-point of that metal. In the experiments in which I have placed platinum wire or sheet in the explosion-vessel, although in nearly all cases the surfaces of the sheet or wire showed signs of fusion, there was only one instance in which the platinum was completely melted, and this was in the case of the explosion of a charge of Spanish powder, which, you will remember, in the heat

experiments developed a larger quantity of heat than any of the other powders.

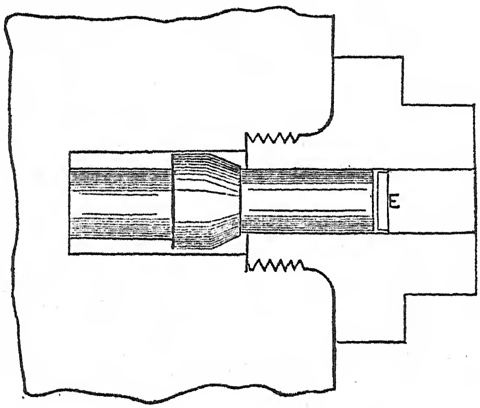
The conclusion I draw from the whole of these experiments with platinum and iridio-platinum is, that since in nearly every case the surface of the metal was melted, or showed signs of fusion, and since in one case (and that the case where we know the greatest heat was developed) the platinum did fully and entirely melt, we may conclude that with these powders the temperature is above the melting-point of platinum, but not very greatly above it.

Now the melting-point of platinum is about 2000° Cent., and of the iridio-platinum still higher. Hence, I should infer from these direct experiments that the temperature of explosion of powders like the W.-A. powders is between 2100° Cent. and 2200° Cent., thus confirming the theoretical determination to which I referred.

The apparatus used for the determination of the tension or pressure existing in the closed cylinder at the moment of explosion is shown in diagram Fig. III., and its action is easily understood. The

Fig. III.

CRUSHER GAUGE.



gauge consists of a small chamber in which is placed a cylinder of copper of fixed dimensions and well-determined hardness. This copper cylinder is acted on by a piston of steel, the piston itself being acted on by the tension of the gases. The pressure corresponding to a given compression of the copper cylinder being known and registered in tables, it is only necessary after each explosion to ascertain the altered length of the small pillars. In the earlier experiments a

single crusher-gauge only was employed; but in nearly all the more recent experiments two or three gauges were used so as to check the accuracy of each determination.

To ensure accurate results with these gauges, certain precautions under varying circumstances have to be carefully attended to, or pressures may be obtained which are very wide of the truth; but as this subject is of great importance and has caused no inconsiderable amount of discussion, I shall endeavour to explain the conditions which under the indications given by the crusher-gauge may be safely relied on.

It will be easily understood that if a pressure of, say, 20 tons per square inch is suddenly applied to the piston, and if this pressure be resisted by a copper pillar which initially is only capable of supporting, without motion, a pressure of 4 tons per square inch, a certain amount of energy will be communicated to the piston, and the copper pillar when taken for measurement will have registered not only the gaseous tension, but, in addition, a pressure corresponding to the energy impressed upon the piston during its motion.

To get rid of this disturbing cause, it has been found necessary, when high pressures are being measured, to employ cylinders which are capable of supporting, without motion, pressures very near to those which it is desired to measure.

Thus, if it be desired to measure expected pressures of 15 tons per square inch, cylinders which would support 14 tons would be selected. If it were desired to measure 20 tons pressures, cylinders of between 18 and 19 tons per square inch would be taken, and so on.

But there is another cause which may seriously affect the indications given by the crusher-gauge. If we could suppose that an explosive was homogeneous, that it filled the chamber of the gun or explosion-vessel in which it was confined completely, that it could be instantaneously and simultaneously exploded right through its mass, and that when so converted into gas or other products of explosion there was no motion of any of the particles; in that case, a properly adjusted crusher-gauge would give an accurate measurement of the pressure; but the actual state of the case is very different. The explosive is generally lighted at a single point. The products of explosion are projected at a very high velocity, occasionally with large charges, through considerable spaces, and impress their energy upon any bodies with which they may come in contact. If that body happen to be the piston of a crusher-gauge, to the mean gaseous pressure existing in the chamber will or may be added the pressure

due to the action I have just explained. I may illustrate my meaning by asking you to imagine the effect of a charge of small shot fired into the crusher-gauge,—the products of explosion projected with a high velocity act in a precisely similar manner.

But there is yet another point to consider. In the ignition of very large charges, especially when the explosive is transformed with great rapidity, it is *à priori* in every way probable that in different sections of the chamber very different pressures may exist, and experiments have shown that this is the case. In such instances the crusher-gauges may give approximately the pressures that actually existed during an infinitesimal portion of time, but such pressures must not be taken as correctly indicating the pressure due to the density and temperature of explosion. It was to escape action of this sort that the very large grain slow-burning powders of the present day were elaborated, and with such powders the pressure in the powder-chamber is also tolerably uniform; but with the old "brisante" powders a portion of the charge was exceedingly rapidly decomposed, the products of explosion were projected with a high velocity to the other end of the chamber, and on striking the shot or other resisting body this *vis viva* was reconverted into pressure, producing intense local pressures. When this intense local action was set up, it commonly happened that waves of pressure swept backwards and forwards from one end of the chamber to the other, and crusher-gauges placed at different points would register the maximum pressure of these waves as they passed.

You will fully understand—I must not detain you by going into great detail—that these high local pressures act only upon a small section of the chamber at the same instant, and therefore are not very serious as far as the radial strength of the gun is concerned. They are however exceedingly serious in breech-loading guns, as the breech screw or other breech arrangement has to sustain the full effect of all such wave action as I have just been describing. In the "brisante" powders of many years ago it was frequently a matter of doubt whether or not this wave action would be set up; but to illustrate my remarks I give you an instance which I have before cited.

In experiments with a 10-inch gun in which a rapidly lighting powder was used, two consecutive rounds were fired, in one of which wave action was set up, in the other not. The two rounds gave practically the same velocity, so that the mean pressure in the bore must have been the same; but five crusher-gauges, three of which

were in the powder-chamber, one in the shot-chamber, and one a few inches in front of the shot-chamber, gave the following results:—

With wave action, 63·4, 41·6, 37·0, 41·9, and 25·8 tons per square inch.

With no wave action, 28·0, 29·8, 30·0, 29·8, and 19·8 tons per square inch.

Chronoscopic observations of the velocity were simultaneously taken in these two rounds, and were, as they ought to be, nearly identical.

When experimenting with high explosives, I have found it necessary to use a special form of gauge; with guncotton, for example, which detonates with great readiness under certain conditions, the gauges were so formed as only to allow the gases to act on the piston after passing through an extremely small hole in a shield or cover protecting the piston.

To illustrate the difference between a gauge protected as I have described, and a gauge such as that shown in Fig. 3, I need only refer to an experiment in which I employed four crusher-gauges, three of which had shielded pistons, and indicated pressures of respectively 32·4, 32·0, and 33·6 tons per square inch. The unshielded gauge, which was placed at the end of the chamber, and was free to receive the full energy of the wave action, indicated 47 tons per square inch, or over 7000 atmospheres.

For similar reasons, although I do not deny that crusher-gauges placed in the chase of a gun may give valuable indications, I still consider that unless confirmed by independent means the accuracy of their results is not to be relied on. Where gases and other products of combustion are in extremely rapid motion, there is always a probability of a portion of these products being forced into the gauge at a high velocity, when too high a pressure would be indicated, and there is a possibility that occasionally a pressure somewhat in defect might also be registered.

The experiments made to determine the tension at various gravimetric densities have been very numerous, and on the whole exceedingly accordant.

The highest density at which I have been perfectly successful in retaining absolutely the products of combustion and obtaining a perfectly satisfactory determination has been unity. Even to obtain these I have at this density had several failures, all arising from the gas at one point or other succeeding in cutting its way out. It is worth while mentioning that although with such explosives as gun-

cotton, cordite, ballistite, etc., the explosion-vessels have been subjected to much higher pressures than with gunpowder, the difficulty in retaining the products is not nearly so great.

The reason probably is, that under the first violent action of the explosion, portions of the non-gaseous products are immediately forced between the surfaces intended to be closed by the pressure. Perfect closure is thus rendered impossible, and the destruction of the surfaces is an immediate consequence.

The tensions obtained in the experiments with service-powders gave for a density of unity a pressure of about 6500 atmospheres, or 43 tons per square inch, the tensions at lower densities representing the pressures, and the axis of abscissæ the densities.

But, having determined the tensions by direct measurement, it became important to ascertain how far these tensions were in accord with those deduced from theoretical considerations.

It is not possible for me here to explain to you the details of the calculations by which the formula connecting the density and the tension is arrived at; but I have placed the theoretical curve and that arrived at from actual experiment in juxtaposition in Fig. IV. (see p. 420), and you will note that the two are practically identical. The figures from which the curve is drawn are given in Table 6.

Table 6.—*Pressures in closed vessels observed and calculated.*

Density of products of combustion.	Volumes of expansion.	Pressures observed in explosion-vessels.	Pressures calculated.
		Tons per sq. inch.	Tons per sq. inch.
·90	1·11	32·46	32·460
·80	1·25	25·03	25·525
·70	1·43	19·09	20·024
·60	1·66	14·39	15·554
·50	2·00	10·69	11·851
·40	2·50	7·75	8·732
·30	3·33	5·33	6·071
·20	5·00	3·26	3·771
·10	10·00	1·47	1·765
·05	20·00	0·70	·855

We are now in a position to give answers to the questions relating to gunpowder which I propounded to you a short time ago, and for the sake of clearness I shall give these answers categorically.

I say, then,—

1. That the substances produced by the explosion of the different natures of gunpowder of which I have to-day spoken are shown in Table 2, and that they occur in the proportions there stated.

2. That, with service-powders, about 57 per cent. by weight of the products of explosion are non-gaseous.

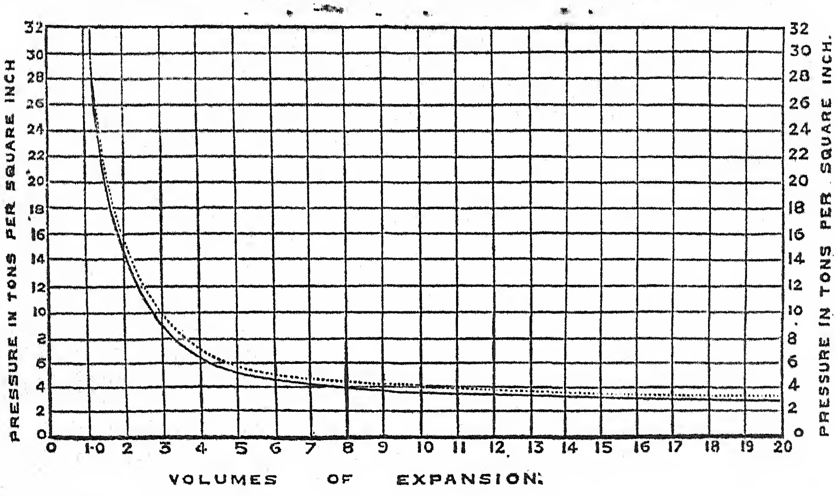
3. That, with the same powders, about 43 per cent. of the products of explosion are in the form of permanent gases, and that these gases, at a temperature of 0° Cent. and at a barometric pressure of 760 mm., occupy about 280 times the volume of the unexploded powder.

4. That, at the moment of explosion, the non-gaseous products are in a liquid state.

5. That a gramme of dry ordinary service-powder, by its explosion, generates about 720 grm.-units of heat.

FIG. IV.

PRESSURES IN CLOSED VESSELS OBSERVED AND CALCULATED



6. That at the moment of explosion the temperature of the products is about 2200° Cent. or nearly 4000° Fahr.

7. That the mean specific heat of the products of explosion at the temperature of explosion is about ·31.

8. That the relation between the tension of the products of explosion and their mean density is as exhibited in the curve in Fig. IV. or Table 6.

9. That the changes produced in the products by a variation in the gravimetric density of the charge are slight—the one of most importance being the increase in the quantity of carbonic acid, and the corresponding decrease in carbonic oxide.

10. That the effect of changes in the chemical composition of gunpowder on its metamorphosis are very considerable, the propor-

tions of the products, the quantity of heat, the amount of permanent gases, being all materially altered, but that these variations do not alter as much as might be expected the tension of the products in relation to the gravimetric density of the charge.

11. That the form and size of the grain affects to some extent the quantity of permanent gases formed, as well as the proportions in which the various products occur.

Guncotton, known also as pyroxylin or trinitro-cellulose, is prepared by submitting cotton to the action of a mixture of concentrated nitric and sulphuric acids, a portion of the hydrogen in the cellulose being replaced by an equivalent quantity of nitric peroxide.

The formula representing guncotton is given in Table 7, and in this table I have also given both the ultimate composition of guncotton and the metamorphosis which it undergoes on explosion. It is employed in several forms. For the most useful, the compressed, and for many other improvements in guncotton, we are indebted to the labours of Sir F. Abel. Several of the forms of guncotton are before me. Here is granulated guncotton, here is guncotton in yarns, strands, and ropes. Here it is in pellets, here in discs, here in slabs; and in these last two forms it is generally used for military and industrial purposes.

TABLE 7.—*Showing the composition and metamorphosis of pellet guncotton.*

Composition.		Products of Explosion.	
Carbon	24·89	Carbonic anhydride	0·424
Hydrogen	2·69	,, oxide	0·280
Nitrogen	13·04	Hydrogen	0·011
Oxygen	56·66	Nitrogen	0·145
Ash	0·36	Marsh-gas	0·003
Moisture	2·36	Water	0·116
Formula—$C_6H_73(NO_2)O_5$.		Original moisture	0·021

I may explain that these last two specimens, which represent considerable quantities of guncotton, are wet, and perfectly safe unless treated in the manner I shall presently describe.

Guncotton differs from gunpowder in this, that when fired, practically the whole of its constituents assume the gaseous state, and the transformation is accompanied by a much higher temperature.

Something is to be learned by observing the ignition. I fire here a piece of yarn; observe the time that the flame takes to traverse the train. Here, again, is a strand: you will note that the ignition is much more rapid, while if I fire this piece of rope you will observe that the rapidity of combustion is so great as to amount almost to an explosion. The slowness of combustion of the yarn and strand gun-

cotton is due to the ease with which the nascent products escape, so that no very high pressure is set up.

The rapidity of combustion of the rope is due to the higher pressure arising from the greater compression and the much larger quantity of gas liberated in a given section.

Were I, by using a few grains of fulminate of mercury, to produce a high initial pressure, the harmless ignition you have seen would be converted into an explosion of the most violent and destructive character. This disc I hold in my hand would blow a hole in a tolerably thick iron plate, and I need not say would make an end of myself and any who had the bad fortune to be very near me.

One great advantage that guncotton possesses lies in the fact that we are able to keep it and use it in the wet state, and in that state to produce quite as effective an explosion as if it were dry. It is only necessary that a few ounces of dry guncotton be in close juxtaposition to the wet, and that the dry guncotton be detonated, as I have described, with a few grains of fulminate of mercury.

I may mention as a curious fact that Sir F. Abel has shown, by means of a chronoscope I shall presently describe, that whereas the detonation of dry guncotton travels at the rate of about 18,000 feet a second, or about 200 miles a minute, the detonation of wet guncotton is at the rate of about 21,000 feet a second, or 240 miles a minute. When the fact is known, it is not difficult to understand the cause of this increased rapidity.

The effect of pressure in increasing the rapidity of combustion of explosives may be very well illustrated by comparing the rapidity of combustion of pebble-powder under different circumstances. A pebble such as I hold in my hand is generally, in the bore of a gun, and under a pressure of from 15 to 20 tons per square inch, entirely consumed in less than the 200th part of a second. In free air the time taken for such a pebble to burn is about two seconds, and *in vacuo* it will not burn at all.

A beautiful experiment for showing this phenomenon has been devised by Sir F. Abel, but for want of the necessary apparatus I am unable to show it here. In an exhausted receiver a platinum wire, which can be heated by an electric battery, is arranged, touching either gunpowder or guncotton. On raising the wire to a red heat the gunpowder or guncotton in contact with the wire burns, but the cooling effect of the immediate expansion of the gases is so great that the combustion is confined to the explosive in actual touch with the heated wire.

The effect of pressure in increasing the rapidity of combustion will enable you to understand the action of fulminate of mercury on guncotton, nitro-glycerine, picric acid, and other high explosives.

I ought to explain that, destructive as are the effects of fired gunpowder, I should not myself include gunpowder in my list of true explosives. It is not like guncotton, nitro-glycerine, and other similar explosives, a definite chemical combination in a state of unstable equilibrium; but it is merely an intimate mixture in proportions which, as you see from Table 1, may be varied to a very considerable extent, of those well-known substances, nitre, sulphur, and charcoal. These constituents do not, during the manufacture of the powder, undergo any chemical change, and being a mere mixture, gunpowder cannot be detonated; but it deflagrates or burns with great rapidity—that rapidity, as I have pointed out, varying largely with the pressure under which the explosion is taking place. Guncotton, on the other hand, when, by means of fulminate of mercury an extremely high local pressure has been set up, transmits that pressure to the adjacent guncotton with extreme rapidity. A charge of pebble-powder in a gun would be consumed in about the 200th part of a second, but a charge of 500 lbs. of these slabs would, if effectively detonated, be converted into gas in somewhere about the 20,000th part of a second.

Reverting again to Table 7, you will observe that carbonic anhydride, carbonic oxide, nitrogen, and water are the principal products of the decomposition of guncotton. The composition of these gases does not vary much with the pressure, but, as in gunpowder, with the higher pressures a larger proportion of carbonic anhydride is formed. The permanent gases, when reduced to 0° Cent. and 760 mm. barometric pressure, measure between two and three times the number of volumes given off by gunpowder, 1 grm. of guncotton generating about 730 c.c. of permanent gas, while the temperature of explosion is at least double that of gunpowder.

From these data it is obvious that the tension of fired guncotton is very high, and, provisionally, I have placed it at about 120 tons per square inch, or nearly 20,000 atmospheres; but all efforts actually to measure with any degree of accuracy these enormous pressures have so far proved futile. The highest pressure I myself have reached was, with a density of ·55, about 70 tons per square inch; but all the crusher-gauges used having been more or less destroyed, this measurement must be accepted with a good deal of reserve.

I have experimented with so many varieties of amide powder

which have differed considerably in their composition, that I would find difficulty in giving you in a few words the somewhat varied results obtained from them.

I shall, therefore, take one only as a sample, and I select this because I shall have occasion, shortly, to refer to some results obtained with it. The powder in question consisted of a mixture of 40 per cent. of potassium nitrate, 38 per cent. of ammonium nitrate, and 22 per cent. of carbon.

Its explosion generates a considerably larger quantity of permanent gases than ordinary powder, and the quantity of heat developed is also greater. The permanent gases consist of 30 per cent. of carbonic acid, 13 per cent. of carbonic oxide, 27 per cent. of hydrogen, and 30 per cent. of nitrogen. The powder cannot truly be called smokeless, but the smoke formed is much less dense and more rapidly dispersed than that of ordinary powder. Its potential energy, as I shall shortly show you, is also much higher, and it further, as far as my experiments on that subject have gone, appears to possess the invaluable property of eroding steel to a much less degree than any other powder with which I have experimented. The main objection to its extended use is the tendency to deliquescence, arising from the use of ammonium nitrate in its composition, and necessitating the powder being kept in air-tight cases. As, however, at all events on board ship, all powders are supposed to be so kept, I do not know that this undoubtedly serious objection would be an insurmountable difficulty if the other advantages of the powder should be fully established.

I come now to the last class of explosive with which I shall trouble you. It is a new explosive, of which you have probably heard, known by the name of "Cordite," and for which we are indebted to Sir F. Abel and Professor Dewar. I have on the table several samples of this explosive. This, which you see looks like a thick thread, is for use in rifles. This size, a little thicker, is used in field guns. These two sizes, like thick cords, a resemblance to which they owe their name, are for 4·7-inch and 6-inch guns.

As with guncotton, I burn one or two lengths. Like guncotton, you will observe there is no smoke; but, unlike guncotton, you will note that there is not the striking difference in the velocity of combustion that you observed with that explosive. I drew your attention to the power we possessed of detonating guncotton by means of fulminate of mercury. This property you will readily understand makes guncotton a most valuable explosive for torpedoes,

or other cases where a maximum of explosive effect is desired; but it unfits it for safe use in large charges in a gun, because under certain abnormal circumstances a detonation might be set up, when the failure of the gun would be the almost infallible consequence. It would be too much at present to say that under no condition is it possible to detonate cordite; but I am able to say that at all events it is in a very high degree less susceptible to detonation than guncotton, and that so far, even by the use of fulminate with the charges with which I have experimented, I have not succeeded in detonating it. The explosive has other advantages; it is, as you see, made in a form specially suitable for making into cartridges. It is not injured by being wetted. I dip it into water, and on removing the superficial water with my handkerchief to allow it to light, you see it burns much as before.

The samples of cordite I have shown you consist approximately of 58 per cent. of guncotton, trinitro- and dinitro-cellulose, 37 per cent. of nitro-glycerine, and a small percentage of a hydrocarbon.

From explosive experiments I have made, it has been found that the products of combustion, which are all gaseous, consist of approximately 27 per cent. of carbonic acid, 34 per cent. of carbonic oxide, 27 per cent. of hydrogen, and 12 per cent. of nitrogen, and to these permanent gases has to be added a considerable quantity of aqueous vapour.

The volume of the permanent gases, at 0° Cent. and 760 mm. barometric pressure, is as nearly as possible 700 c.c. per gramme of cordite, while the quantity of heat developed is 1260 grm.-units. These figures show that the potential energy of this explosive must be very high, as will be demonstrated to you when I come to treat of its action in a gun.

On the diagram Fig. V. I exhibit to you the pressures that I have measured with this explosive up to gravimetric densities of ·55. For purposes of comparison, I have placed on the same diagram the corresponding curve for gunpowder, and you will note how with the cordite the pressures are much higher in relation to density. With this explosive I have made experiments at higher densities than are shown on the curve, and have in fact measured pressures up to 90 tons per square inch; but certain anomalies and difficulties in the interpretation of the results prevent my relying on their exactness until confirmatory experiments have been made.

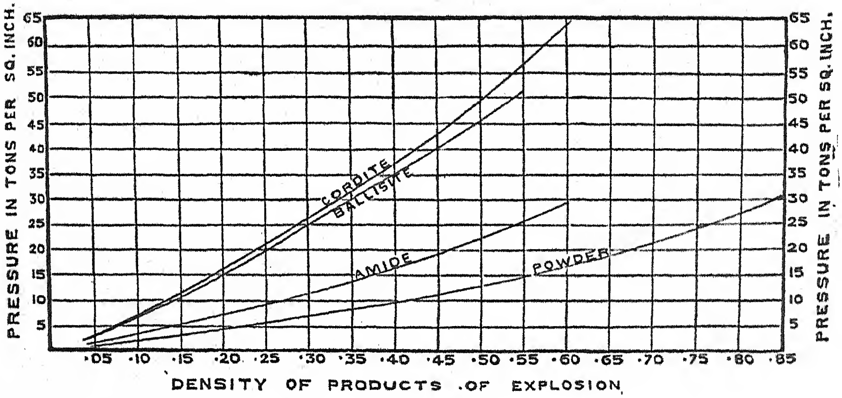
I believe I mentioned to you that ballistite, an explosive of something of the same nature as cordite, is now being introduced on the

Continent for military purposes. In appearance it is very different, as you will see from the samples on the table; but it possesses the same property of smokeless combustion. The gases generated are the same as those of cordite in somewhat different proportions, but their quantity is less, being about 615 c.c. per gramme, while the quantity of heat is higher, being 1356 grm.-units. The potential energy is somewhat less than that of cordite, and I have placed on the same diagram as the cordite the pressures with ballistite for different densities.

I return to gunpowder, which we shall now consider under very different conditions, and shall study the behaviour of a charge when placed in the chamber of a gun, and allowed to act upon a projectile.

Fig. V.

PRESSURES OBSERVED IN CLOSED VESSELS WITH VARIOUS EXPLOSIVES.



You will remember, and forgive me for repetition, that the charge when fully exploded, and at the moment of explosion, consists of about 57 per cent. of liquid products in an extremely fine state of division, and about 43 per cent. of permanent gases; also that when the gravimetric density of the charge is unity the tension when unrelieved by expansion is 6770 atmospheres, or 43 tons per square inch.

Let us suppose in the first instance that the gravimetric density of the charge is unity, and that the charge is entirely consumed before the projectile is removed from its seat. Now under these circumstances, if we represent the relation between the tension and volume occupied by that charge in the bore by a curve, representing the tensions by the ordinates, the volumes or the distances travelled

by the shot corresponding to these volumes by the abscissæ, you will at once see that the curve will be of the form shown in the diagram Fig. IV. This curve, in fact, is the same as that indicated in the diagram Fig. V., and represents the relation between the tensions and densities of the products of combustion, where the gases expand without cooling or production of work; but the densities, instead of being as in the former curve taken as the independent or equicrescent variable, are here dependent on the volume, or numbers of expansions occupied by the charge in the bore, these expansions in this instance being taken as the independent variable.

The maximum tension under the circumstances supposed would, as I have said, be 43 tons per square inch, but the tensions at other points would not, for reasons I shall explain later on, be as great as are shown on this curve.

But many of you are aware that in reality, and especially with the slow-burning powders now introduced for large guns, we cannot consider the charge to be instantaneously exploded, and although the determination of a theoretic curve of pressures to include the first moments of combustion would be a work of the very greatest difficulty, it is yet tolerably easy to see what the general form of this curve of pressures must be.

The charge of powder is generally ignited at a single point. No doubt, especially with pebble, P_2, or prismatic powders, the flame is very rapidly communicated to all the grains, pebbles, or prisms. In each individual pebble, supposing it to be ignited on the whole of its surface, the burning surface is of course a maximum at its first ignition; but the quantity of gases generated will depend so much on the pressure at any particular moment, that it does not necessarily follow that the greatest quantity of gas is given off at the moment when there is the largest burning surface.

Be this as it may, however, it is obvious that before the charge is fully consumed there will be a great decrement in the quantity of gases given off, unless, as in prismatic and some other powders, arrangements are made by means of holes to keep as large as possible the ignited surfaces, or unless the interior of the large pebbles is composed of more explosive and easily broken up material.

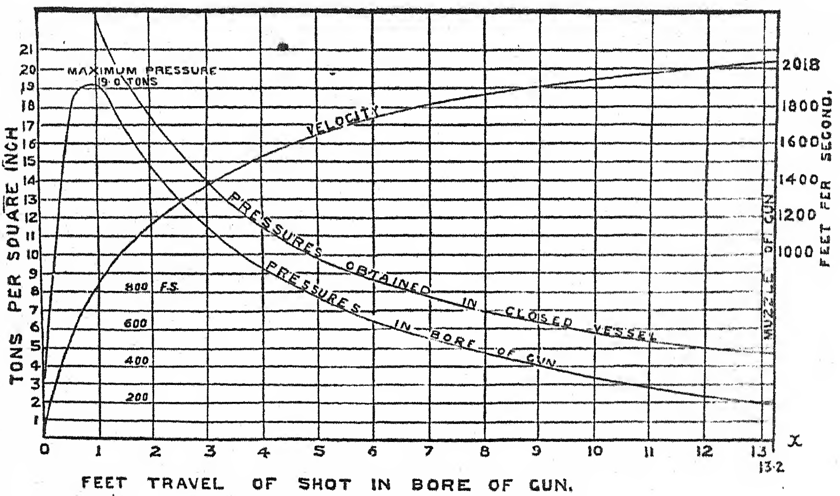
The pressure, then, when the charge is ignited commences, with muzzle-loading guns, at zero; with breech loading-guns, with a pressure of 2 to 4 tons per square inch, or with whatever pressure may be necessary to force the driving-ring of the projectile into the grooves and into the bore of the gun. The pressure increases at an

extremely rapid rate until the maximum increment is reached. It still goes on increasing, but at a rate gradually becoming slower, until the maximum tension is reached, and this tension is attained when the increase of density of the gases due to the combustion of the powder is just balanced by the decrease of density due to the motion of the projectile. After the maximum tension is reached the pressure decreases, at first very rapidly, subsequently slower and slower.

Now, if these variations in pressure be represented by a curve, it is easy to see that the curve will commence at the origin by being convex to the axis of the abscissæ. It will then become concave, then convex, and will finally be asymptotic to the axis of x. It will be in general form similar to the gun-pressure curve shown on the diagram Fig. VI.

Fig. VI.

DIAGRAM SHOWING THE FORMS OF PRESSURE AND VELOCITY CURVES IN A GUN, AND OF CURVE OF PRESSURES IN A CLOSED VESSEL.



In like manner, the curve representing the velocity in the bore of a gun would commence by being convex to the axis of abscissæ. It will then become concave, and were the bore long enough, would be finally asymptotic to a line parallel to the axis of x. The velocity curve is shown in the same diagram, Fig. VI.

Such, then, would be the general form of these curves. Let me now describe to you the means which have been taken to obtain the data necessary for the construction of such curves by actual observation.

It is obvious that if we desired to know the pressure exercised by the gases on the projectile at various points of the bore, the velocities of the projectiles at the same points, and the times taken by the projectile to reach these points from the commencement of motion, there are two courses open to us. We may either, first by suitably prepared gauges (if it be possible to construct such gauges) determine the pressure at various points of the bore, from the pressures deduce the velocities, and thence the times, or we may follow the inverse method. We may measure the times at which the projectile passes certain known points in the bore. From these times we may calculate the corresponding velocities, and finally calculate the pressures necessary to produce these velocities at all points along the bore.

Now, both these methods have been followed, and I shall endeavour to describe the instruments and methods in as few words as possible.

To Rodman, as far as I know, is due the merit of having first used a pressure-gauge to determine the pressure in the bore of a gun. Rodman's own experiments with his gauge are, however, as I have elsewhere shown, unreliable, his pressures being generally much higher than any possible actual pressures, since the pressures given by him as existing at various points along the bore would, if assumed to act on the projectile, give energies in some cases nearly three times as great as in reality.

In this country the crusher-gauge I have already described is almost universally employed. The results it gives are, with proper precautions, reliable when the gauge is placed in the chamber; but it cannot, as I have endeavoured to explain, be depended upon with any accuracy when placed in positions where the products of explosion are moving at a high velocity.

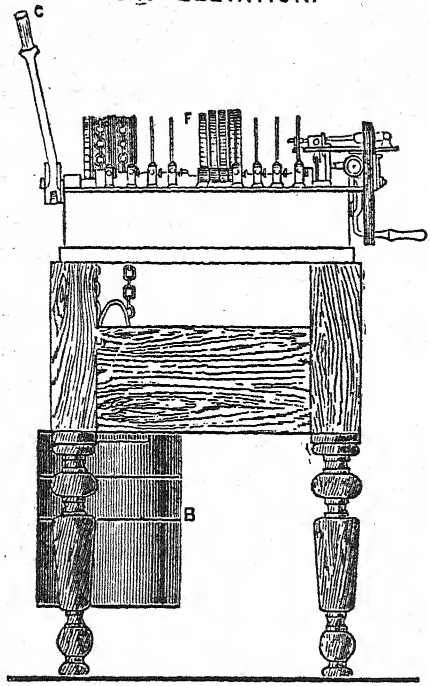
Two methods have been employed for obtaining the pressure by the inverse method. One method consisted in shortening the gun by successive calibres, and at each length determining the velocity imparted to the projectile by the same charge.

This method, however, is a very rude one, and is open to several very serious objections, and a preferable method is to measure the time at which the projectile passes certain fixed points in the bore. To effect this object a chronograph was employed, with certain peculiarities of construction designed to measure very minute intervals of time.

This instrument is shown in the diagrams Figs. VII., VIII., and IX.

It consists of a series of thin discs, each 36 inches in circumference, made to rotate at a very high and uniform velocity through the train of wheels F by means of a heavy descending weight B, arranged, to avoid an inconvenient length of chain, upon a plan originally proposed by Huyghens, the weight being, during the experiment, continually wound up by the handle C, and thus the instrument can be made to travel either quite uniformly or at a rate very slowly increasing or decreasing. The speed with which the circumference of the discs travels is usually about 1200 inches per second; an inch, therefore, represents the 1200th part of a second; and as by means of a vernier we are able to divide the inch into 1000 parts, the instrument is capable of recording less than the one millionth part of a second. You will appreciate the extreme minuteness of this portion of time, if I point out that the millionth of a second is about the same fraction of a second that a second is of a fortnight. The precise rate of the discs is ascertained by means of the intermediate shaft, which in the earlier arrangement worked a stop clock, but in the more recent, by means of a relay, registers the revolutions on a subsidiary chronoscope (each revolution of the intermediate shaft corresponding to 200 revolutions of the discs), upon which subsidiary chronoscope a chronometer, also by means of a relay, registers seconds.

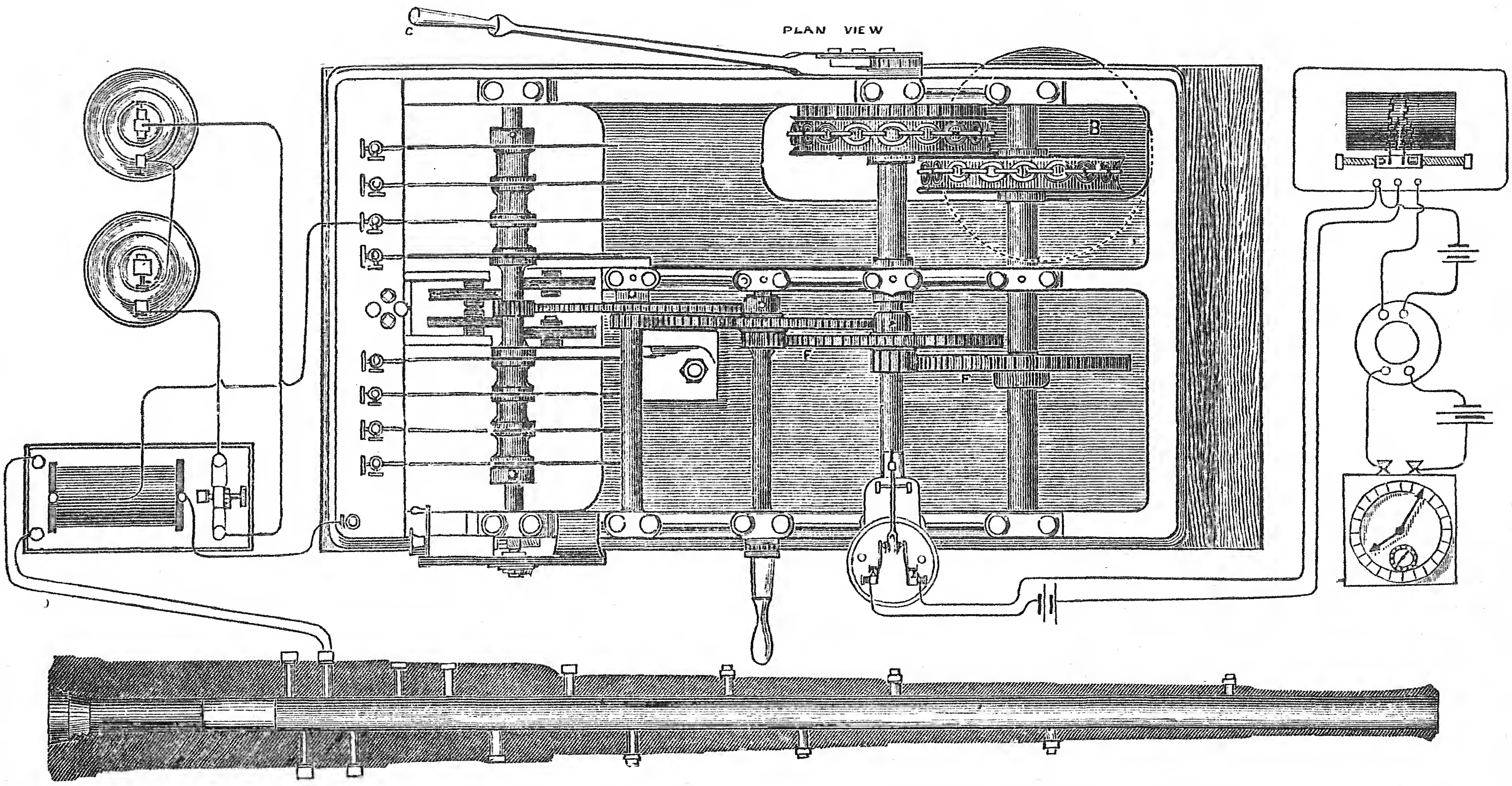
Fig. VIII.
END ELEVATION.



The recording arrangement is as follows. The peripheries of the discs we cover with specially prepared paper, and each disc is provided with an induction coil. You are aware that when the primary of an induction coil is suddenly severed, a spark, under proper management, is given off from the secondary, and in the arrangement I am describing the severance of the primary is caused

Fig. VII.

CHRONOSCOPE



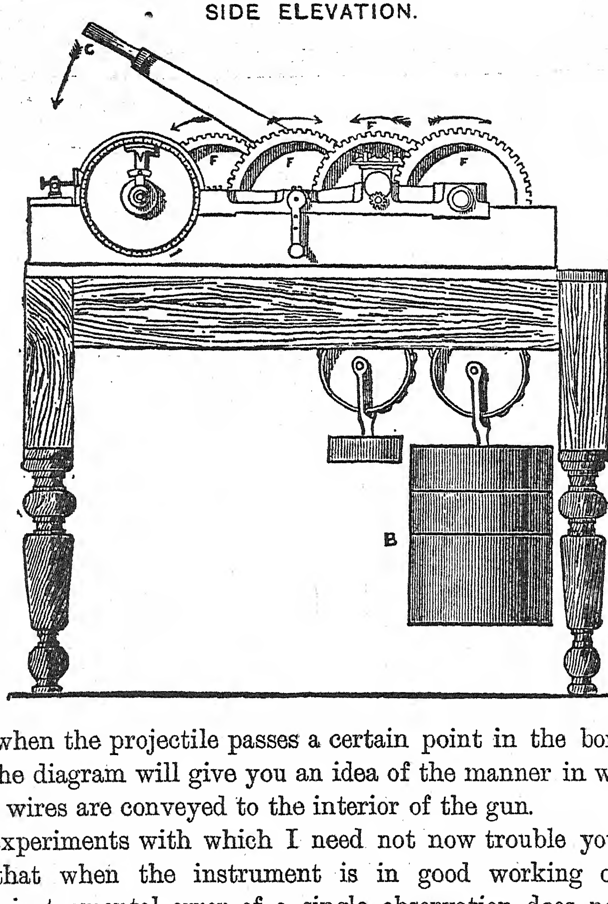
[To face p. 430.

by the shot in its passage through the bore, and as each successive wire is cut the induction coils record on their own discs the instant at which the shot cuts the wire, that is, passes the particular point with which the primary wire is connected.

To prevent confusion, there is delineated in the diagram only a single induction coil and cell; but you will understand that there is an induction coil for each disc, and that each disc, discharger, and cell form, so to speak, independent instruments for recording the

Fig. IX.

SIDE ELEVATION.



instant when the projectile passes a certain point in the bore of the gun. The diagram will give you an idea of the manner in which the primary wires are conveyed to the interior of the gun.

By experiments with which I need not now trouble you, I have found that when the instrument is in good working order the probable instrumental error of a single observation does not exceed from two to three millionths of a second.

Let me now give you some of the actual results obtained by the means I have just described.

I have given you a short account of two or three of the more

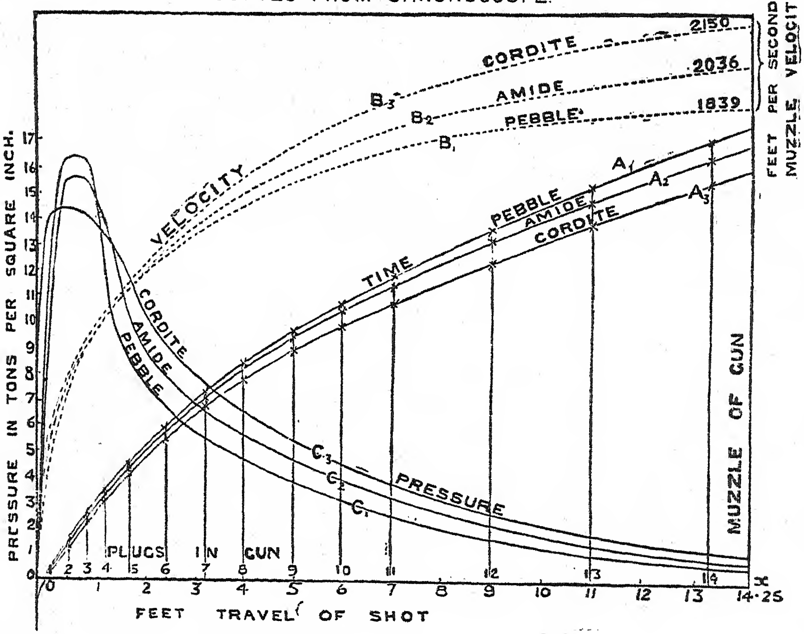
modern explosives—I mean amide powder, cordite, and ballistite—and have, I fear, somewhat wearied you with the details into which I have gone in respect to the old powder.

Now on this diagram, Fig. X., are exhibited the results obtained with three of these powders, all fired from the same gun, under the same conditions, with approximately the same maximum pressures; but, as you see, with very different results as regards velocity and energy.

You will note that the axis of abscissæ, Ox, denotes the length of

FIG. X.

CURVES FROM CHRONOSCOPE.



the bore of the gun traversed by the shot under the action of the explosion, and that the ordinates to the crosses on the curves A_1, A_2, A_3 denote the times occupied by the shot in reaching the various points shown. The total time taken by the shot in traversing the whole bore is ·01 second in the case of pebble-powder, ·0095 seconds with amide powder, and ·009 seconds with cordite.

The velocities at all points of the bore are indicated by the curves B_1, B_2, B_3, and you see that the muzzle velocity of ordinary powder is 1839 feet per second, of amide powder 2036 feet per second, and cordite 2150 feet per second.

In like manner, the pressures at all points of the bore are shown by the curves C_1, C_2, C_3. Observe that the maximum pressure with pebble-powder is 16·4 tons per square inch, with amide powder 16 tons per square inch, and with cordite 14·4 tons per square inch. The area between the curves C, the axis of abscissæ Ox, and the ordinate at the muzzle represent for each curve the energy developed by that explosive in the bore. It is easy by mere inspection to see that the total energy of the amide powder and of the cordite is much higher than that developed by the pebble; but if we make the required calculations and put the result in figures, we shall find that the energy developed by the pebble-powder was 1055 foot-tons, by the amide 1293 foot-tons, and by the cordite 1435 foot-tons, or, with less maximum pressure, nearly 40 per cent. higher than in the case of pebble-powder, and an examination of the pressure curves will show in what portions of the bore this great additional energy is realised.

It is important to observe that these greatly higher energies developed by the modern powders are obtained with considerably reduced charges, the weight of the charge of amide powder being reduced to 85 per cent., and of cordite to 47 per cent. of that used when the service pebble-powder is employed.

These results have been obtained by actual experiment, and it remains to ascertain what accordance there is between them and what we have a right to expect from theoretical considerations.

Taking, again, gunpowder as our illustration; Hutton appears to have been the first person who attempted anything like a theoretical explanation of the action of gunpowder on a projectile, but he not unnaturally fell into the error of assuming that the whole of the products were in a gaseous state, and, further, that their tension was directly proportional to the density, and inversely as the space they occupied. In other words, he supposed that the gases in expanding and performing work accomplished that work without expenditure of heat.

De Saint Robert, who was the first to apply to the question the modern theory of thermo-dynamics, corrected Hutton's error, but, like Hutton, he assumed that the whole of the products were in a gaseous state, and, as gases, doing work on the projectile.

Bunsen and Schischkoff, in their well-known researches on gunpowder, pointed out that although it was probable that there might be a slight volatilisation of the solid products, yet it was in the highest degree improbable that such volatilisation would ever reach a single atmosphere of pressure, and that any effect on the projectile

would be perfectly insignificant. They therefore, in their calculations, disregarded the solid residue altogether, and calculated the total work which gunpowder is capable of performing on the assumption that such work is done by the expansion of the gases alone without addition or subtraction of heat, and that, in fact, the non-gaseous products played no part in the expansion.

The effect of these erroneous assumptions was that the tensions calculated on De Saint Robert's hypothesis were considerably higher (for given densities) than those which were observed in a close vessel where the gases expand without production of work, while the tensions calculated on Bunsen and Schischkoff's hypothesis were greatly in defect, not only when the tensions were taken from those observed in a close vessel, but also in defect of the pressures actually observed in the bores of guns.

At an earlier stage in the researches carried on by Sir F. Abel and myself, I came to the conclusion, when I found that the pressures deduced from experiments in close vessels did not differ so much as I anticipated from those taken in the bores of guns, that this departure from expectation was probably due to the heat stored up in the liquid residue; and it must be noted that this liquid residue being in an exceedingly finely divided state, and thoroughly mixed up with gases, constitutes a source of heat of the most perfect character, immediately available for compensating the cooling effect due to the expansion of the gases when employed in the production of work.

On correcting the assumptions I have referred to, and calculating the tensions that would exist in the bore of a gun, it was found that the anomalies to which I have drawn your attention were entirely removed, and that theory and observation were in accord, the pressures obtained with Waltham-Abbey powder being, even while the densities were still very high, not greatly removed from the theoretic curve, while when the powder may be considered entirely consumed the two curves slide into one another, and for all practical purposes become coincident.

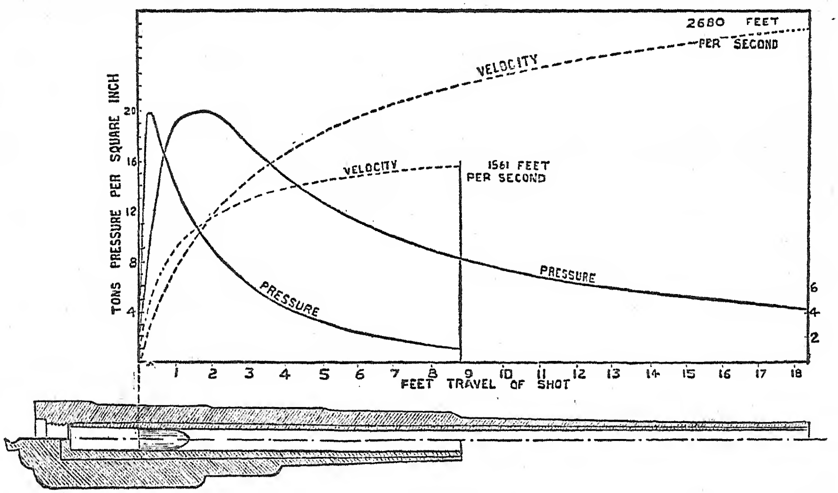
In my address to the mechanical section of the British Association, I drew attention to the extraordinary stagnation that had existed in guns and artillery during a period of more than two centuries—a stagnation that was the more remarkable because the mind of this country during the long period of the Napoleonic and earlier wars must have been to a large extent fixed on everything connected with our Naval and Military Services.

It is not too much to say that the changes and improvements in artillery made during the ten years that followed the Crimean War far exceeded in importance all the improvements made during the previous 200 years.

What the future may produce it is difficult to say; but to show you that during the last ten or fifteen years great progress has been made both in guns and the explosives which are used in them, I draw your attention to the results obtained from a 7-inch 7-ton rifled gun of fifteen years ago and those obtained from a 6-inch $6\frac{1}{2}$-ton quick-firing gun with a charge of cordite. To show you the difference in the appearance of the guns, I have placed side by side half sections of

FIG. XI.

COMPARISON BETWEEN A 7-INCH OLD GUN AND A 6-INCH NEW GUN



the two guns (see Fig. XI.). Note the difference in the length of the guns. Taking first the velocity curves, note the enormous difference in velocity, the old gun having a velocity of 1560 feet per second, while no less than 2680 feet per second were realised with the 6-inch. But the energy of the projectile shows in the most striking way the difference between the guns. The maximum pressure being about the same, the energy of the 7-inch projectile is only 1943 foot-tons, while that of the 6-inch gun is 5000 foot-tons, or not far off three times as great.

To emphasise what I have said as to the magnitude of the advances in artillery that have been made since 1856, it is enough to point out that since that date the charges of gunpowder fired in guns have

increased from 16 to 1000 lbs., the weights of the projectiles from 68 to 2000 lbs., the velocities from 1600 feet per second to 2700 feet per second,* and the energies developed in the projectiles from 1100 foot-tons to 62,000 foot-tons.

In referring to the diagram to which I just now called your attention, I pointed out the great difference in the length of the two guns compared, but I am bound to admit that as a thermo-dynamic machine the old guns were more economical than the new ones; the reason being, that as the charges are proportionally much larger in the new ones, the tension of the gas at the muzzle is also larger, and the products are discharged with a larger proportion of their total energy unrealised.

It may interest you to know what this total energy amounts to. Knowing the permanent gases formed, knowing also the specific heats and the tensions at the moment of explosion, the ordinary laws of thermo-dynamics enable us to calculate the total energy which will be developed.

In the case of gunpowder the calculation is somewhat complicated by the large proportion of non-gaseous products, but, as I have elsewhere shown, with certain modifications the ordinary laws are applicable, and the total energy obtainable if the charge be indefinitely expanded is about 34,000 kilogrammetres per kilogramme of powder or, in English measure, nearly 500 foot-tons per pound of powder.

Cordite would give, approximately, under the same conditions, a total energy four times as great, or, say, 2000 foot-tons per pound of cordite.

When we consider the destructive effects realisable by even a small charge of gunpowder, it is somewhat surprising to reflect that this potential energy of gunpowder is only about one-tenth of that of one pound of coal, and is not even equal to the energy stored up in the carbon which forms one of its own constituents.

At the same time, it must not be forgotten that the gunpowder has stored up in it the oxygen necessary for the oxidation of its carbon and other oxidisable substances, while one pound of carbon, in burning to carbonic acid, has to draw from the air nearly 3 lbs. of oxygen.

You may, possibly, desire to know what proportion of the total theoretic work of gunpowder is realised in modern artillery.

* Were it necessary, with our new explosives still higher velocities and energies might be obtained. The highest possible velocity, however, interesting as it may be in a scientific, is not always desirable in a practical point of view.

A gun being, as I have said, an extremely simple form of the thermo-dynamic engine, the coefficient of effect is high. The actual energy realised varies considerably, dependent on circumstances, but may be taken as something between 50 and 90 foot-tons per pound of powder, or, say, from about one-tenth to one-fifth of the total theoretic effect. The average coefficient of effect, comparing the energy expressed in the projectile with that due to the expansion of the gases, may, I think, be taken as somewhere near 80 per cent. It rarely falls below 70 per cent., and, occasionally, with large guns and charges, is considerably above 90 per cent.

But I must conclude, and conclude as I began, by emphasising the indebtedness of my own department, as well as of nearly all departments of knowledge, to the great man whose anniversary my lecture to-night is intended to commemorate.

It must ever be a subject of pride to this country that the two inventions—I mean the steam engine and the locomotive—which in my judgment have done far more than any other which can be named to advance civilisation and the welfare of the human race, are due to her sons.

These inventions have for some generations brought to this country great wealth, and employment for thousands upon thousands. But other nations are now running us close, and unless the patient industry, laborious search after truth, and energy in overcoming difficulties, which were the distinguishing characteristics of James Watt and George Stephenson, be preserved in some degree among all classes in the generation which shall carry on our work, the days of England's manufacturing pre-eminence are numbered.

In the following table I have given the values of certain constants which are of common occurrence in questions connected with "Internal Ballistics." This table requires no explanation, but to it I have added some other tables which I have calculated, and which in my own work I have found exceedingly useful.

These tables are as follow:—First, a table giving the work in foot-tons that 1 lb. of service gunpowder is capable of performing, in expanding from a volume whose gravimetric density is unity, to any given number of volumes, up to forty. As an example of the use of this table, suppose that in an 8-inch gun, a charge of 100 lbs. of powder, with a gravimetric density of unity, is fired, and suppose further, that the number of expansions that this charge suffers, when the base of the projectile reaches the muzzle, is 4·29; what is the

maximum energy that the powder is capable of generating? From the table it will be seen that the work corresponding to an expansion of 4·29 volumes is 85·068 foot-tons per lb. of powder, and as the charge is supposed to be 100 lbs., the maximum energy, under the conditions stated, which that charge would be capable of generating, would be 8506·8 foot-tons. The maximum effect is of course never realised, and for proved powders a factor of effect is generally approximately known. If we suppose this factor to be 0·84; then $8506{\cdot}8 \times 0{\cdot}84 = 7145{\cdot}7$ foot-tons represents the energy which will be realised. Should the density not be unity, a correction has to be made. Thus if the gravimetric density of the charge were 0·87, which density corresponds to 1·15 volumes of expansion, from the value 85·068 foot-tons per lb. of powder given above, would have to be subtracted* 12·625 foot-tons, the energy due to the expansion of 1·15 volumes, the maximum energy realisable would be $(85{\cdot}068 - 12{\cdot}625)\ 100 = 7244{\cdot}3$ foot-tons, while assuming the same factor of effect, the energy which would be actually realised would be 6085 foot-tons.

The second table gives the energy in foot-tons stored up in 1 lb. in weight, moving at any velocity, up to 3000 feet per second. For example, if we desired to know the energy stored up in a 100-lb. shot moving with a velocity of 2182 feet per second, from the table we see that that energy is 3301·4 foot-tons; or if we wished to know the velocity with which a projectile 200 lbs. weight, possessing 7145·7 foot-tons energy, was moving, $\frac{7145{\cdot}7}{200} = 35{\cdot}7285$, and from the table the velocity required is 2270 feet per second.

Tables 3 and 4 differ from Tables 2 and 1 only in the metre and kilogramme being employed to replace the foot and pound as the units of length and weight.

Table 5 is for converting cubic inches per pound of powder into densities and volumes, and *vice versâ*.

* See *Phil. Trans. of the Roy. Soc.*, part i., 1880.

Table of numbers frequently required in ballistic calculations.

	No.	Log.	Log.	No.	
Inch in a millimetre	0·03937043	$\overline{2}$·595170	1·404830	25·39977	Millimetres in an inch.
Feet in a metre	3·2808693	0·515989	$\overline{1}$·484011	0·30479721	Metre in a foot.
Square inch in a square mm.	·00155003	$\overline{3}$·190340	2·809660	645·1483	Square mm. in a square inch.
Square inch in a square cm.	·155003	$\overline{1}$·190340	0·809660	6·451483	Square cm. in a square inch.
Cub. inches in cubic decimetre = cubic inches in a litre	61·025377	1·785511	$\overline{2}$·214489	·0163866	Litre, or cubic decimetre in a cubic inch.
Grains in a pound avoirdupois	7000	3·845098	$\overline{4}$·154902	·000142857	Pound in a grain.
Grains in a gramme	15·43235	1·188432	$\overline{2}$·811568	·064799	Gramme in a grain.
Pounds avoirdupois in a kilogramme	2·20462	0·343334	$\overline{1}$·656666	·453593	Kilogramme in a pound.
Pounds avoirdupois in a ton	2240	3·350248	$\overline{4}$·649752	·00044643	Ton in a pound.
Ton in a tonne	·984206	$\overline{1}$·993086	0·006914	1·01605	Tonne in a ton.
Pounds avoirdupois in a tonne	2204·62144	3·343334	$\overline{4}$·656666	·00045359	Tonne in a pound.
Cubic inch in a cubic mm.	0·000061025	$\overline{5}$·785511	4·214489	16387	Cubic mm. in a cubic inch.
Cubic inches in a gallon	277·11726	2·442664	$\overline{3}$·557336	·00360858	Gallon in a cubic inch.
Gallon in a litre	·220215	$\overline{1}$·342847	0·657153	4·54102	Litres in a gallon.
π	3·1415927	0·497150	$\overline{1}$·502850	·3183098S	$\frac{1}{\pi}$
Foot-tons in a metre tonne	3·22005	0·509075	$\overline{1}$·490925	·3096885	Metre tonne in a foot-ton.
Foot-pounds in a kilogrammetre	7·23308	0·859323	$\overline{1}$·140677	·138254	Kilogrammetre in a foot-pound.
Pounds per square inch, to a kilog. per sq. millimetre	1422·31	3·152994	$\overline{4}$·847006	·000703083	Kilogramme per sq. millimetre in a pound per sq. inch.
Tons per sq. inch per kilog. per sq. centimetre . .	·00634959	$\overline{3}$·802746	2·197254	157·4906	Kilogrammes per sq. cm. in a ton per sq. inch.
Fahrenheit degrees in a Centigrade degree . . .	1·8	0·255273	$\overline{1}$·744727	·55556	Centigrade degree in a Fahrenheit degree.
Cubic inches in a pound of water at 0° Cent. . .	27·684	1·442229	$\overline{2}$·557771	·03612195	Pound of water in a cubic inch at 0° Cent.
Cubic inches in a pound of water at maximum density	27·680	1·442166	$\overline{2}$·557834	·03612717	Pound of water in a cubic inch at maximum density.
Pounds of water in a cubic foot at 0° Cent. . . .	62·418	1·795310	$\overline{2}$·204690	·01602102	Cubic foot in a pound of water at 0° Cent.
Pounds of water in a cubic foot at maximum density .	62·425	1·795359	$\overline{2}$·204641	·01601922	Cubic foot in a pound of water at maximum density.
Specific gravity of mercury at 0° Cent.	13·59593	1·133409	$\overline{2}$·866591		
Pounds per sq. inch in 1 atmosphere (760 mm. mercury at 0° Cent.)	14·694805	1·167164	$\overline{2}$·832836		
Atmospheres in a ton per square inch	152·43482	2·183084	$\overline{3}$·816916	·0065602	Tons per square inch in 1 atmosphere.
"g." in latitude of London	32·19078	1·507732	$\overline{2}$·492268		
2 g.	64·38156	1·808762	$\overline{2}$·191238		
2 g. 2240	144214·694	5·159009	$\overline{6}$·840991		
Modulus of common logarithms	0·4342945	$\overline{1}$·6377843	0·3622157		

Table showing the work in foot-tons that 1 lb. of gunpowder is capable of performing in expanding from volume = 1, to any given number of volumes up to 40.

Volumes.	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09
	Work in Foot-tons.					Work in Foot-tons.				
1·0	0·000	·978	1·934	2·868	3·780	4·672	5·545	6·399	7·234	8·051
·1	8·852	9·637	10·406	11·160	11·899	12·625	13·338	14·038	14·725	15·400
·2	16·063	16·716	17·359	17·992	18·614	19·226	19·828	20·420	21·003	21·577
·3	22·142	22·699	23·248	23·789	24·323	24·850	25·370	25·882	26·388	26·887
·4	27·380	27·867	28·348	28·823	29·291	29·753	30·211	30·663	31·109	31·550
·5	31·986	32·417	32·843	33·264	33·681	34·093	34·500	34·903	35·301	35·695
·6	36·086	36·473	36·855	37·233	37·608	37·979	38·346	38·709	39·069	39·425
·7	39·778	40·128	40·474	40·817	41·156	41·493	41·827	42·158	42·486	42·811
·8	43·133	43·452	43·769	44·083	44·394	44·703	45·009	45·313	45·614	45·913
·9	46·209	46·503	46·795	47·085	47·372	47·657	47·940	48·221	48·500	48·776
2·0	49·050	49·321	49·590	49·857	50·121	50·383	50·643	50·902	51·160	51·417
·1	51·673	51·927	52·179	52·429	52·677	52·923	53·167	53·410	53·652	53·893
·2	54·132	54·370	54·606	54·840	55·073	55·304	55·534	55·762	55·989	56·215
·3	56·439	56·662	56·883	57·103	57·322	57·539	57·755	57·970	58·183	58·395
·4	58·605	58·814	59·022	59·229	59·435	59·639	59·842	60·044	60·245	60·444
·5	60·642	60·839	61·035	61·230	61·424	61·616	61·807	61·997	62·186	62·375
·6	62·563	62·750	62·936	63·121	63·304	63·486	63·667	63·848	64·028	64·207
·7	64·385	64·562	64·738	64·913	65·088	65·262	65·435	65·607	65·778	65·949
·8	66·119	66·288	66·456	66·623	66·789	66·955	67·120	67·284	67·447	67·609
·9	67·771	67·932	68·092	68·251	68·410	68·568	68·725	68·882	68·938	69·093
3·0	69·347	69·501	69·654	69·806	69·958	70·109	70·259	70·409	70·558	70·706
·1	70·854	71·001	71·148	71·294	71·440	71·585	71·730	71·874	72·017	72·159
·2	72·301	72·442	72·583	72·723	72·863	73·002	73·141	73·279	73·417	73·554
·3	73·690	73·826	73·962	74·097	74·231	74·365	74·498	74·631	74·764	74·896
·4	75·027	75·158	75·289	75·419	75·548	75·677	75·805	75·933	76·061	76·188
·5	76·315	76·441	76·566	76·691	76·816	76·940	77·064	77·187	77·310	77·432
·6	77·553	77·674	77·795	77·916	78·036	78·156	78·275	78·394	78·513	78·631
·7	78·749	78·866	78·983	79·100	79·216	79·332	79·447	79·562	79·677	79·791
·8	79·905	80·019	80·132	80·245	80·357	80·469	80·581	80·692	80·803	80·914
·9	81·024	81·134	81·244	81·353	81·462	81·570	81·678	81·786	81·893	82·000
4·0	82·107	82·213	82·319	82·425	82·530	82·635	82·740	82·845	82·949	83·053
·1	83·157	83·260	83·363	83·466	83·568	83·670	83·772	83·873	83·974	84·075
·2	84·176	84·276	84·376	84·476	84·575	84·674	84·773	84·872	84·970	85·068
·3	85·166	85·263	85·360	85·457	85·554	85·650	85·746	85·842	85·938	86·033
·4	86·128	86·223	86·317	86·411	86·505	86·599	86·692	86·785	86·878	86·971
·5	87·064	87·156	87·248	87·340	87·432	87·523	87·614	87·705	87·795	87·885
·6	87·975	88·065	88·154	88·243	88·332	88·421	88·509	88·597	88·685	88·773
·7	88·861	88·948	89·035	89·122	89·209	89·295	89·381	89·467	89·553	89·639
·8	89·724	89·809	89·894	89·979	90·063	90·147	90·231	90·315	90·399	90·482
·9	90·565	90·648	90·731	90·814	90·896	90·978	91·060	91·142	91·223	91·304
5·0	91·385	91·466	91·547	91·628	91·708	91·788	91·868	91·948	92·028	92·107
·1	92·186	92·265	92·344	92·423	92·501	92·579	92·657	92·735	92·813	92·891
·2	92·968	93·045	93·122	93·199	93·276	93·352	93·428	93·504	93·580	93·656
·3	93·732	93·807	93·882	93·957	94·032	94·107	94·182	94·257	94·331	94·405
·4	94·479	94·553	94·627	94·701	94·774	94·847	94·920	94·993	95·066	95·138
	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09

Table showing the work in foot-tons that 1 *lb. of gunpowder, etc.*—continued.

Volumes.	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09
	Work in Foot-tons.					Work in Foot-tons.				
5·5	95·210	95·282	95·354	95·426	95·498	95·570	95·641	95·712	95·783	95·854
·6	95·925	95·996	96·066	96·136	96·206	96·276	96·346	96·416	96·486	96·556
·7	96·625	96·694	96·763	96·832	96·901	96·970	97·038	97·106	97·174	97·242
·8	97·310	97·378	97·446	97·513	97·580	97·647	97·714	97·781	97·848	97·915
·9	97·981	98·047	98·113	98·179	98·245	98·311	98·377	98·443	98·508	98·573
6·0	98·638	98·703	98·768	98·833	98·898	98·962	99·026	99·090	99·154	99·218
·1	99·282	99·346	99·410	99·474	99·537	99·600	99·663	99·726	99·789	99·852
·2	99·915	99·978	100·041	100·103	100·165	100·227	100·289	100·351	100·413	100·475
·3	100·536	100·598	100·659	100·721	100·782	100·843	100·904	100·965	101·025	101·085
·4	101·145	101·205	101·265	101·325	101·385	101·445	101·505	101·565	101·625	101·685
·5	101·744	101·803	101·862	101·921	101·980	102·039	102·098	102·157	102·216	102·275
·6	102·333	102·391	102·449	102·507	102·565	102·623	102·681	102·739	102·797	102·855
·7	102·912	102·969	103·026	103·083	103·140	103·197	103·254	103·311	103·368	103·424
·8	103·480	103·536	103·592	103·648	103·704	103·760	103·816	103·872	103·928	103·983
·9	104·038	104·093	104·148	104·203	104·258	104·313	104·368	104·423	104·478	104·532
7·0	104·586	104·640	104·694	104·748	104·802	104·856	104·910	104·964	105·018	105·072
·1	105·125	105·178	105·231	105·284	105·337	105·390	105·443	105·496	105·549	105·602
·2	105·655	105·708	105·760	105·812	105·864	105·916	105·968	106·020	106·072	106·124
·3	106·176	106·228	106·280	106·331	106·382	106·433	106·484	106·535	106·586	106·637
·4	106·688	106·739	106·790	106·841	106·892	106·942	106·992	107·042	107·092	107·142
·5	107·192	107·242	107·292	107·342	107·392	107·442	107·492	107·541	107·590	107·639
·6	107·688	107·737	107·786	107·835	107·884	107·933	107·982	108·031	108·080	108·129
·7	108·177	108·226	108·274	108·323	108·371	108·419	108·467	108·515	108·563	108·611
·8	108·659	108·707	108·755	108·803	108·851	108·898	108·945	108·992	109·039	109·086
·9	109·133	109·180	109·227	109·274	109·321	109·368	109·415	109·462	109·508	109·554
8·0	109·600	109·646	109·692	109·738	109·784	109·830	109·876	109·922	109·968	110·014
·1	110·060	110·106	110·152	110·198	110·244	110·289	110·334	110·379	110·424	110·469
·2	110·514	110·559	110·604	110·649	110·694	110·739	110·784	110·829	110·873	110·918
·3	110·962	111·007	111·051	111·096	111·140	111·184	111·228	111·272	111·316	111·360
·4	111·404	111·448	111·492	111·536	111·580	111·624	111·668	111·711	111·754	111·797
·5	111·840	111·883	111·926	111·969	112·012	112·055	112·098	112·141	112·184	112·227
·6	112·270	112·313	112·356	112·399	112·442	112·485	112·527	112·569	112·611	112·653
·7	112·695	112·737	112·779	112·821	112·863	112·905	112·947	112·989	113·031	113·073
·8	113·114	113·156	113·197	113·239	113·280	113·322	113·363	113·405	113·446	113·487
·9	113·528	113·569	113·610	113·651	113·692	113·733	113·774	113·815	113·856	113·897
9·0	113·937	113·978	114·018	114·059	114·099	114·140	114·180	114·221	114·261	114·301
·1	114·341	114·381	114·421	114·461	114·501	114·541	114·581	114·621	114·660	114·700
·2	114·739	114·779	114·818	114·858	114·897	114·937	114·976	115·016	115·055	115·094
·3	115·133	115·172	115·211	115·250	115·289	115·328	115·367	115·405	115·444	115·482
·4	115·521	115·559	115·598	115·636	115·675	115·713	115·752	115·790	115·829	115·867
·5	115·905	115·943	115·981	116·019	116·057	116·095	116·133	116·171	116·209	116·247
·6	116·284	116·322	116·359	116·397	116·434	116·472	116·509	116·547	116·584	116·622
·7	116·659	116·696	116·733	116·770	116·807	116·844	116·881	116·918	116·955	116·992
·8	117·029	117·066	117·103	117·140	117·176	117·213	117·249	117·286	117·332	117·359
·9	117·395	117·432	117·468	117·505	117·541	117·577	117·613	117·649	117·685	117·721
	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09

Table showing the work in foot-tons that 1 *lb. of gunpowder, etc.*—continued.

Volumes.	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9
	Work in Foot-tons.					Work in Foot-tons.				
10·0	117·757	118·114	118·468	118·818	119·164	119·506	119·845	120·180	120·512	120·840
11	121·165	121·486	121·804	122·119	122·431	122·739	123·045	123·347	123·646	123·944
12	124·239	124·531	124·820	125·107	125·391	125·671	125·949	126·224	126·507	126·777
13	127·036	127·302	127·566	127·828	128·088	128·346	128·602	128·856	129·107	129·356
14	129·602	129·846	130·089	130·330	130·570	130·809	131·040	131·281	131·513	131·743
15	131·970	132·195	132·419	132·642	132·863	133·083	133·302	133·520	133·737	133·953
16	134·168	134·382	134·594	134·804	135·012	135·218	135·422	135·624	135·824	136·022
17	136·218	136·413	136·608	136·802	136·995	137·187	137·379	137·570	137·760	137·949
18	138·138	138·326	138·513	138·698	138·881	139·063	139·243	139·421	139·597	139·771
19	139·944	140·117	140·289	140·461	140·632	140·803	140·973	141·143	141·312	141·480
20	141·647	141·813	141·977	142·140	142·302	142·463	142·623	142·782	142·941	143·099
21	143·258	143·415	143·571	143·726	143·880	144·033	144·186	144·338	144·489	144·639
22	144·788	144·937	145·085	145·233	145·380	145·526	145·671	145·815	145·958	146·100
23	146·242	146·383	146·524	146·664	146·803	146·942	147·080	147·218	147·355	147·492
24	147·629	147·765	147·900	148·035	148·169	148·302	148·435	148·567	148·699	148·830
25	148·960	149·090	149·219	149·348	149·476	149·603	149·730	149·856	149·982	150·107
26	150·232	150·356	150·480	150·603	150·726	150·848	150·970	151·091	151·212	151·332
27	151·452	151·571	151·690	151·808	151·926	152·043	152·160	152·276	152·392	152·507
28	152·622	152·736	152·850	152·963	153·076	153·188	153·300	153·411	153·522	153·633
29	153·743	153·852	153·961	154·069	154·177	154·285	154·393	154·500	154·607	154·713
30	154·819	154·925	155·030	155·135	155·239	155·343	155·447	155·550	155·653	155·755
31	155·857	155·959	156·060	156·161	156·262	156·362	156·461	156·560	156·659	156·758
32	156·856	156·954	157·052	157·150	157·247	157·344	157·441	157·537	157·633	157·729
33	157·824	157·919	158·014	158·108	158·202	158·296	158·390	158·483	158·586	158·679
34	158·771	158·863	158·955	159·046	159·137	159·228	159·319	159·409	159·499	159·589
35	159·678	159·767	159·856	159·944	160·032	160·120	160·208	160·295	160·382	160·469
36	160·556	160·643	160·729	160·815	160·901	160·987	161·072	161·157	161·242	161·327
37	161·411	161·495	161·579	161·663	161·746	161·829	161·912	161·995	162·077	162·159
38	162·241	162·323	162·404	162·485	162·566	162·647	162·727	162·807	162·887	162·967
39	163·046	163·125	163·204	163·283	163·361	163·439	163·517	163·595	163·673	163·751
40	163·828									
	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9

Table giving in foot-tons the energy stored up in 1 lb. in weight, moving at any velocity between 10 and 3000 feet per second.

Velocity.		1	2	3	4	5	6	7	8	9
10	·0007	·0008	·0010	·0012	·0014	·0016	·0018	·0020	·0022	·0025
20	·0028	·0031	·0034	·0037	·0040	·0043	·0047	·0050	·0054	·0058
30	·0062	·0067	·0071	·0076	·0080	·0085	·0090	·0095	·0100	·0105
40	·0111	·0117	·0122	·0128	·0134	·0140	·0147	·0153	·0160	·0166
50	·0173	·0180	·0187	·0194	·0201	·0209	·0217	·0225	·0233	·0241
60	·0250	·0258	·0267	·0275	·0284	·0293	·0302	·0311	·0321	·0330
70	·0339	·0349	·0359	·0369	·0380	·0390	·0400	·0411	·0422	·0433
80	·0444	·0455	·0466	·0477	·0489	·0501	·0513	·0525	·0537	·0549
90	·0561	·0574	·0587	·0600	·0613	·0626	·0639	·0652	·0665	·0679
100	·0693	·0707	·0721	·0735	·0749	·0764	·0779	·0794	·0809	·0824
110	·0839	·0854	·0870	·0885	·0901	·0917	·0933	·0949	·0965	·0982
120	·0999	·1015	·1032	·1049	·1066	·1083	·1101	·1118	·1136	·1154
130	·1172	·1190	·1208	·1226	·1245	·1264	·1283	·1301	·1321	·1340
140	·1359	·1379	·1398	·1418	·1438	·1458	·1478	·1498	·1519	·1539
150	·1560	·1581	·1602	·1623	·1644	·1666	·1687	·1709	·1731	·1753
160	·1775	·1797	·1820	·1842	·1865	·1888	·1911	·1934	·1957	·1980
170	·2004	·2028	·2051	·2075	·2099	·2124	·2148	·2172	·2197	·2222
180	·2247	·2272	·2297	·2322	·2348	·2373	·2399	·2425	·2451	·2477
190	·2503	·2530	·2556	·2583	·2610	·2637	·2664	·2691	·2718	·2746
200	·2774	·2801	·2829	·2857	·2886	·2914	·2942	·2971	·3000	·3029
210	·3058	·3087	·3116	·3146	·3176	·3205	·3235	·3265	·3295	·3326
220	·3356	·3387	·3417	·3448	·3479	·3510	·3542	·3573	·3604	·3636
230	·3668	·3700	·3732	·3764	·3797	·3829	·3862	·3895	·3928	·3961
240	·3994	·4027	·4061	·4095	·4128	·4162	·4196	·4230	·4265	·4299
250	·4334	·4369	·4403	·4438	·4474	·4509	·4544	·4580	·4616	·4651
260	·4687	·4724	·4760	·4796	·4833	·4869	·4906	·4943	·4980	·5018
270	·5055	·5092	·5130	·5168	·5206	·5244	·5282	·5320	·5359	·5397
280	·5436	·5475	·5514	·5553	·5593	·5632	·5672	·5712	·5751	·5791
290	·5832	·5872	·5912	·5953	·5994	·6034	·6075	·6116	·6158	·6199
300	·6241	·6282	·6324	·6366	·6408	·6450	·6493	·6535	·6578	·6621
310	·6664	·6707	·6750	·6793	·6837	·6880	·6924	·6968	·7012	·7056
320	·7100	·7145	·7190	·7234	·7279	·7324	·7369	·7415	·7460	·7506
330	·7551	·7597	·7643	·7689	·7735	·7782	·7828	·7875	·7922	·7969
340	·8016	·8063	·8110	·8158	·8205	·8253	·8301	·8349	·8397	·8446
350	·8494	·8542	·8591	·8640	·8689	·8738	·8788	·8837	·8887	·8936
360	·8986	·9036	·9086	·9136	·9187	·9238	·9289	·9339	·9390	·9441
370	·9493	·9544	·9596	·9647	·9698	·9751	·9803	·9855	·9908	·9960
380	1·0013	1·0066	1·0118	1·0171	1·0225	1·0278	1·0331	1·0385	1·0439	1·0493
390	1·0547	1·0601	1·0655	1·0710	1·0764	1·0819	1·0873	1·0929	1·0984	1·1039
400	1·1095	1·1150	1·1206	1·1262	1·1318	1·1374	1·1430	1·1486	1·1543	1·1599
410	1·1656	1·1713	1·1770	1·1827	1·1884	1·1942	1·2000	1·2058	1·2115	1·2174
420	1·2232	1·2290	1·2348	1·2407	1·2466	1·2525	1·2584	1·2643	1·2702	1·2762
430	1·2821	1·2881	1·2941	1·3005	1·3061	1·3121	1·3181	1·3242	1·3303	1·3363
440	1·3424	1·3485	1·3547	1·3608	1·3670	1·3731	1·3793	1·3855	1·3917	1·3979
		1	2	3	4	5	6	7	8	9

Table of energies—continued.

Velocity.		1	2	3	4	5	6	7	8	9
440	1·3424	1·3485	1·3547	1·3608	1·3670	1·3731	1·3793	1·3855	1·3917	1·3979
450	1·4042	1·4104	1·4167	1·4229	1·4292	1·4355	1·4418	1·4482	1·4545	1·4609
460	1·4673	1·4736	1·4800	1·4865	1·4929	1·4993	1·5058	1·5122	1·5187	1·5252
470	1·5317	1·5383	1·5448	1·5514	1·5579	1·5645	1·5711	1·5777	1·5843	1·5910
480	1·5976	1·6043	1·6110	1·6176	1·6243	1·6311	1·6378	1·6445	1·6513	1·6581
490	1·6649	1·6717	1·6785	1·6853	1·6922	1·6990	1·7059	1·7128	1·7197	1·7266
500	1·7335	1·7405	1·7474	1·7544	1·7614	1·7684	1·7754	1·7824	1·7894	1·7964
510	1·8036	1·8106	1·8177	1·8248	1·8320	1·8391	1·8462	1·8534	1·8606	1·8678
520	1·8750	1·8822	1·8894	1·8967	1·9039	1·9112	1·9185	1·9258	1·9331	1·9404
530	1·9478	1·9551	1·9625	1·9699	1·9773	1·9847	1·9921	1·9996	2·0070	2·0145
540	2·0220	2·0295	2·0370	2·0445	2·0520	2·0596	2·0672	2·0747	2·0823	2·0899
550	2·0976	2·1052	2·1128	2·1205	2·1282	2·1359	2·1436	2·1513	2·1590	2·1668
560	2·1745	2·1823	2·1901	2·1979	2·2057	2·2135	2·2214	2·2292	2·2371	2·2450
570	2·2529	2·2608	2·2687	2·2767	2·2846	2·2926	2·3006	2·3086	2·3166	2·3246
580	2·3326	2·3407	2·3487	2·3568	2·3649	2·3730	2·3811	2·3893	2·3974	2·4056
590	2·4138	2·4219	2·4302	2·4384	2·4466	2·4548	2·4631	2·4714	2·4797	2·4880
600	2·4963	2·5046	2·5129	2·5213	2·5297	2·5380	2·5464	2·5549	2·5633	2·5717
610	2·5802	2·5886	2·5971	2·6056	2·6141	2·6226	2·6312	2·6397	2·6483	2·6569
620	2·6655	2·6741	2·6827	2·6913	2·7000	2·7086	2·7173	2·7260	2·7347	2·7434
630	2·7521	2·7610	2·7696	2·7784	2·7872	2·7960	2·8048	2·8136	2·8225	2·8313
640	2·8402	2·8491	2·8580	2·8669	2·8758	2·8847	2·8937	2·9027	2·9117	2·9206
650	2·9297	2·9387	2·9477	2·9568	2·9658	2·9749	2·9840	2·9931	3·0022	3·0113
660	3·0205	3·0296	3·0388	3·0480	3·0572	3·0664	3·0757	3·0849	3·0942	3·1034
670	3·1127	3·1220	3·1313	3·1406	3·1500	3·1593	3·1687	3·1781	3·1875	3·1969
680	3·2063	3·2157	3·2258	3·2347	3·2442	3·2537	3·2632	3·2727	3·2822	3·2918
690	3·3013	3·3109	3·3205	3·3301	3·3397	3·3493	3·3590	3·3686	3·3783	3·3880
700	3·3977	3·4074	3·4171	3·4269	3·4366	3·4464	3·4562	3·4660	3·4758	3·4856
710	3·4955	3·5053	3·5152	3·5251	3·5350	3·5449	3·5548	3·5647	3·5747	3·5847
720	3·5946	3·6046	3·6146	3·6247	3·6347	3·6447	3·6548	3·6649	3·6750	3·6851
730	3·6952	3·7053	3·7155	3·7256	3·7358	3·7460	3·7562	3·7664	3·7766	3·7869
740	3·7971	3·8074	3·8177	3·8280	3·8383	3·8486	3·8589	3·8693	3·8797	3·8900
750	3·9004	3·9108	3·9213	3·9317	3·9421	3·9526	3·9631	3·9736	3·9841	3·9946
760	4·0051	4·0157	4·0262	4·0368	4·0474	4·0580	4·0686	4·0792	4·0898	4·1005
770	4·1112	4·1219	4·1326	4·1433	4·1540	4·1648	4·1755	4·1863	4·1971	4·2079
780	4·2187	4·2295	4·2404	4·2512	4·2621	4·2730	4·2839	4·2948	4·3057	4·3166
790	4·3276	4·3385	4·3495	4·3605	4·3715	4·3825	4·3934	4·4044	4·4155	4·4266
800	4·4378	4·4489	4·4600	4·4712	4·4823	4·4935	4·5046	4·5158	4·5270	4·5382
810	4·5495	4·5607	4·5720	4·5832	4·5945	4·6058	4·6171	4·6284	4·6398	4·6511
820	4·6625	4·6739	4·6853	4·6967	4·7081	4·7195	4·7310	4·7424	4·7539	4·7654
830	4·7769	4·7884	4·7999	4·8115	4·8230	4·8346	4·8462	4·8578	4·8694	4·8811
840	4·8927	4·9044	4·9160	4·9277	4·9394	4·9511	4·9628	4·9745	4·9863	4·9981
850	5·0099	5·0217	5·0335	5·0453	5·0571	5·0690	5·0809	5·0927	5·1046	5·1165
860	5·1285	5·1404	5·1523	5·1643	5·1763	5·1883	5·2003	5·2123	5·2243	5·2364
870	5·2483	5·2604	5·2725	5·2846	5·2967	5·3088	5·3209	5·3330	5·3452	5·3574
880	5·3696	5·3818	5·3940	5·4062	5·4185	5·4308	5·4431	5·4554	5·4677	5·4800
		1	2	3	4	5	6	7	8	9

Table of energies—continued.

Velocity.		1	2	3	4	5	6	7	8	9
880	5·3696	5·3818	5·3940	5·4062	5·4185	5·4308	5·4431	5·4554	5·4677	5·4800
890	5·4925	5·5048	5·5172	5·5296	5·5420	5·5544	5·5668	5·5792	5·5917	5·6041
900	5·6166	5·6291	5·6416	5·6541	5·6666	5·6792	5·6918	5·7043	5·7169	5·7295
910	5·7421	5·7547	5·7674	5·7800	5·7927	5·8054	5·8181	5·8308	5·8435	5·8563
920	5·8690	5·8818	5·8946	5·9074	5·9202	5·9330	5·9458	5·9587	5·9715	5·9844
930	5·9973	6·0102	6·0231	6·0360	6·0490	6·0620	6·0749	6·0879	6·1009	6·1139
940	6·1270	6·1400	6·1531	6·1661	6·1792	6·1923	6·2054	6·2186	6·2317	6·2448
950	6·2580	6·2712	6·2844	6·2976	6·3108	6·3241	6·3373	6·3506	6·3639	6·3772
960	6·3905	6·4038	6·4171	6·4305	6·4438	6·4572	6·4700	6·4840	6·4974	6·5108
970	6·5243	6·5377	6·5512	6·5647	6·5782	6·5917	6·6052	6·6187	6·6324	6·6459
980	6·6595	6·6731	6·6867	6·7003	6·7140	6·7276	6·7413	6·7550	6·7687	6·7824
990	6·7961	6·8098	6·8236	6·8374	6·8512	6·8649	6·8787	6·8926	6·9064	6·9202
1000	6·9341	6·9480	6·9619	6·9758	6·9897	7·0036	7·0176	7·0315	7·0455	7·0595
1010	7·0735	7·0875	7·1015	7·1156	7·1296	7·1437	7·1578	7·1719	7·1860	7·2001
1020	7·2142	7·2284	7·2426	7·2567	7·2709	7·2851	7·2994	7·3136	7·3278	7·3421
1030	7·3564	7·3706	7·3850	7·3993	7·4136	7·4279	7·4423	7·4567	7·4711	7·4855
1040	7·4999	7·5143	7·5288	7·5433	7·5577	7·5722	7·5867	7·6012	7·6157	7·6302
1050	7·6448	7·6594	7·6740	7·6886	7·7032	7·7178	7·7325	7·7471	7·7617	7·7764
1060	7·7911	7·8059	7·8206	7·8353	7·8501	7·8648	7·8796	7·8944	7·9092	7·9240
1070	7·9388	7·9537	7·9686	7·9834	7·9983	8·0132	8·0281	8·0431	8·0580	8·0730
1080	8·0879	8·1029	8·1179	8·1329	8·1480	8·1630	8·1780	8·1931	8·2082	8·2233
1090	8·2384	8·2535	8·2687	8·2838	8·2990	8·3142	8·3294	8·3446	8·3598	8·3750
1100	8·3903	8·4055	8·4208	8·4361	8·4514	8·4667	8·4820	8·4974	8·5127	8·5281
1110	8·5435	8·5590	8·5743	8·5897	8·6052	8·6206	8·6361	8·6516	8·6671	8·6826
1120	8·6981	8·7137	8·7292	8·7448	8·7604	8·7760	8·7916	8·8072	8·8228	8·8385
1130	8·8541	8·8698	8·8855	8·9012	8·9169	8·9327	8·9484	8·9642	8·9800	8·9958
1140	9·0116	9·0274	9·0432	9·0590	9·0749	9·0908	9·1067	9·1226	9·1385	9·1544
1150	9·1703	9·1863	9·2023	9·2183	9·2343	9·2503	9·2663	9·2823	9·2984	9·3144
1160	9·3305	9·3466	9·3627	9·3788	9·3950	9·4111	9·4273	9·4435	9·4597	9·4759
1170	9·4921	9·5083	9·5246	9·5408	9·5571	9·5734	9·5897	9·6060	9·6223	9·6387
1180	9·6550	9·6714	9·6878	9·7042	9·7206	9·7370	9·7535	9·7699	9·7864	9·8029
1190	9·8194	9·8359	9·8524	9·8690	9·8855	9·9021	9·9186	9·9352	9·9518	9·9685
1200	9·9851	10·0018	10·0184	10·0351	10·0518	10·0685	10·0852	10·1019	10·1187	10·1354
1210	10·1522	10·1690	10·1858	10·2026	10·2194	10·2363	10·2531	10·2700	10·2869	10·3038
1220	10·3207	10·3376	10·3546	10·3715	10·3885	10·4055	10·4225	10·4395	10·4565	10·4735
1230	10·4906	10·5077	10·5247	10·5418	10·5589	10·5761	10·5932	10·6103	10·6275	10·6447
1240	10·6619	10·6791	10·6963	10·7135	10·7308	10·7483	10·7653	10·7826	10·7999	10·8172
1250	10·8345	10·8519	10·8692	10·8866	10·9040	10·9214	10·9388	10·9562	10·9737	10·9911
1260	11·0086	11·0261	11·0436	11·0611	11·0786	11·0961	11·1137	11·1312	11·1488	11·1664
1270	11·1840	11·2016	11·2193	11·2369	11·2546	11·2722	11·2899	11·3076	11·3254	11·3431
1280	11·3608	11·3786	11·3964	11·4141	11·4319	11·4498	11·4676	11·4854	11·5033	11·5211
1290	11·5390	11·5569	11·5748	11·5928	11·6107	11·6287	11·6466	11·6646	11·6826	11·7006
1300	11·7186	11·7367	11·7547	11·7728	11·7909	11·8089	11·8271	11·8452	11·8633	11·8814
1310	11·8996	11·9178	11·9360	11·9542	11·9724	11·9906	12·0089	12·0271	12·0454	12·0637
1320	12·0820	12·1003	12·1186	12·1370	12·1553	12·1737	12·1921	12·2105	12·2289	12·2473
		1	2	3	4	5	6	7	8	9

Table of energies—continued.

Velocity.		1	2	3	4	5	6	7	8	9
1320	12·0820	12·1003	12·1186	12·1370	12·1553	12·1737	12·1921	12·2105	12·2289	12·2473
1330	12·2657	12·2842	12·3026	12·3211	12·3396	12·3581	12·3766	12·3952	12·4137	12·4323
1340	12·4509	12·4695	12·4881	12·5067	12·5253	12·5440	12·5626	12·5813	12·6000	12·6187
1350	12·6374	12·6561	12·6749	12·6936	12·7124	12·7312	12·7500	12·7688	12·7876	12·8065
1360	12·8253	12·8442	12·8631	12·8820	12·9009	12·9198	12·9387	12·9577	12·9766	12·9956
1370	13·0146	13·0336	13·0526	13·0717	13·0907	13·1098	13·1289	13·1479	13·1671	13·1862
1380	13·2053	13·2244	13·2436	13·2628	13·2820	13·3012	13·3204	13·3396	13·3588	13·3781
1390	13·3974	13·4167	13·4360	13·4553	13·4746	13·4939	13·5133	13·5327	13·5520	13·5714
1400	13·5908	13·6103	13·6297	13·6491	13·6686	13·6881	13·7076	13·7271	13·7466	13·7661
1410	13·7857	13·8052	13·8248	13·8444	13·8640	13·8836	13·9033	13·9229	13·9426	13·9622
1420	13·9819	14·0016	14·0213	14·0411	14·0608	14·0806	14·1003	14·1201	14·1399	14·1597
1430	14·1795	14·1994	14·2192	14·2391	14·2590	14·2789	14·2988	14·3187	14·3386	14·3586
1440	14·3785	14·3985	14·4185	14·4385	14·4585	14·4786	14·4986	14·5187	14·5388	14·5588
1450	14·5789	14·5991	14·6192	14·6393	14·6595	14·6797	14·6998	14·7200	14·7403	14·7605
1460	14·7807	14·8010	14·8213	14·8415	14·8618	14·8821	14·9025	14·9228	14·9432	14·9635
1470	14·9839	15·0043	15·0247	15·0451	15·0656	15·0860	15·1065	15·1269	15·1474	15·1579
1480	15·1885	15·2090	15·2295	15·2501	15·2707	15·2913	15·3119	15·3325	15·3531	15·3737
1490	15·3944	15·4151	15·4358	15·4564	15·4772	15·4979	15·5186	15·5394	15·5601	15·5809
1500	15·6017	15·6225	15·6434	15·6642	15·6850	15·7059	15·7268	15·7477	15·7686	15·7895
1510	15·8104	15·8314	15·8524	15·8733	15·8943	15·9153	15·9363	15·9574	15·9784	15·9995
1520	16·0205	16·0416	16·0627	16·0838	16·1050	16·1261	16·1473	16·1684	16·1896	16·2108
1530	16·2320	16·2533	16·2745	16·2958	16·3170	16·3383	16·3596	16·3809	16·4022	16·4236
1540	16·4449	16·4663	16·4877	16·5090	16·5305	16·5519	16·5733	16·5948	16·6162	16·6377
1550	16·6592	16·6807	16·7022	16·7237	16·7453	16·7668	16·7884	16·8100	16·8316	16·8532
1560	16·8748	16·8965	16·9181	16·9398	16·9615	16·9832	17·0049	17·0266	17·0483	17·0701
1570	17·0919	17·1136	17·1354	17·1572	17·1791	17·2009	17·2228	17·2446	17·2665	17·2884
1580	17·3103	17·3322	17·3541	17·3761	17·3980	17·4200	17·4420	17·4640	17·4860	17·5081
1590	17·5301	17·5522	17·5742	17·5963	17·6184	17·6405	17·6627	17·6848	17·7069	17·7291
1600	17·7513	17·7735	17·7957	17·8179	17·8402	17·8624	17·8847	17·9070	17·9293	17·9516
1610	17·9739	17·9962	18·0186	18·0409	18·0633	18·0857	18·1081	18·1305	18·1529	18·1754
1620	18·1979	18·2203	18·2428	18·2653	18·2879	18·3104	18·3329	18·3555	18·3780	18·4006
1630	18·4232	18·4458	18·4684	18·4911	18·5137	18·5364	18·5591	18·5818	18·6045	18·6272
1640	18·6500	18·6727	18·6955	18·7182	18·7410	18·7638	18·7867	18·8095	18·8323	18·8552
1650	18·8781	18·9010	18·9239	18·9468	18·9697	18·9927	19·0156	19·0386	19·0616	19·0846
1660	19·1076	19·1306	19·1537	19·1767	19·1998	19·2229	19·2460	19·2691	19·2922	19·3154
1670	19·3385	19·3617	19·3849	19·4081	19·4313	19·4545	19·4777	19·5010	19·5242	19·5475
1680	19·5708	19·5941	19·6174	19·6408	19·6641	19·6875	19·7108	19·7342	19·7576	19·7810
1690	19·8045	19·8279	19·8514	19·8749	19·8983	19·9218	19·9454	19·9689	19·9924	20·0160
1700	20·0395	20·0631	20·0867	20·1103	20·1340	20·1576	20·1813	20·2049	20·2286	20·2523
1710	20·2760	20·2997	20·3235	20·3472	20·3710	20·3947	20·4185	20·4423	20·4662	20·4900
1720	20·5138	20·5377	20·5614	20·5855	20·6094	20·6333	20·6572	20·6812	20·7051	20·7291
1730	20·7531	20·7771	20·8011	20·8251	20·8491	20·8732	20·8973	20·9214	20·9454	20·9696
1740	20·9937	21·0178	21·0420	21·0661	21·0903	21·1145	21·1387	21·1629	21·1872	21·2114
1750	21·2357	21·2600	21·2842	21·3086	21·3329	21·3572	21·3815	21·4059	21·4303	21·4547
1760	21·4791	21·5035	21·5279	21·5524	21·5768	21·6013	21·6258	21·6503	21·6748	21·6993
		1	2	3	4	5	6	7	8	9

Table of energies—continued.

Velocity.		1	2	3	4	5	6	7	8	9
1760	21·4791	21·5035	21·5279	21·5524	21·5768	21·6013	21·6258	21·6503	21·6748	21·6993
1770	21·7238	21·7484	21·7730	21·7975	21·8221	21·8467	21·8714	21·8960	21·9207	21·9453
1780	21·9700	21·9947	22·0194	22·0441	22·0689	22·0936	22·1184	22·1431	22·1679	22·1927
1790	22·2175	22·2424	22·2672	22·2921	22·3170	22·3418	22·3667	22·3917	22·4166	22·4415
1800	22·4665	22·4915	22·5164	22·5414	22·5664	22·5914	22·6165	22·6416	22·6666	22·6917
1810	22·7168	22·7419	22·7670	22·7922	22·8173	22·8425	22·8677	22·8929	22·9181	22·9432
1820	22·9685	22·9938	23·0190	23·0443	23·0696	23·0949	23·1202	23·1455	23·1709	23·1962
1830	23·2216	23·2470	23·2724	23·2978	23·3232	23·3487	23·3741	23·3996	23·4251	23·4506
1840	23·4761	23·5016	23·5272	23·5527	23·5783	23·6038	23·6294	23·6550	23·6806	23·7063
1850	23·7320	23·7576	23·7833	23·8090	23·8347	23·8604	23·8861	23·9119	23·9377	23·9634
1860	23·9892	24·0150	24·0408	24·0667	24·0925	24·1184	24·1442	24·1701	24·1960	24·2219
1870	24·2478	24·2738	24·2997	24·3257	24·3517	24·3777	24·4037	24·4297	24·4558	24·4818
1880	24·5079	24·5340	24·5601	24·5862	24·6123	24·6384	24·6646	24·6907	24·7169	24·7431
1890	24·7693	24·7955	24·8217	24·8480	24·8743	24·9005	24·9268	24·9531	24·9794	25·0058
1900	25·0321	25·0585	25·0848	25·1112	25·1376	25·1640	25·1904	25·2169	25·2433	25·2698
1910	25·2963	25·3228	25·3493	25·3758	25·4024	25·4289	25·4555	25·4820	25·5086	25·5352
1920	25·5618	25·5885	25·6151	25·6418	25·6685	25·6952	25·7219	25·7486	25·7753	25·8021
1930	25·8288	25·8556	25·8824	25·9092	25·9360	25·9628	25·9897	26·0165	26·0434	26·0703
1940	26·0972	26·1241	26·1510	26·1780	26·2049	26·2319	26·2589	26·2858	26·3129	26·3399
1950	26·3669	26·3940	26·4210	26·4481	26·4752	26·5023	26·5294	26·5566	26·5837	26·6109
1960	26·6380	26·6652	26·6924	26·7196	26·7469	26·7741	26·8014	26·8287	26·8559	26·8832
1970	26·9105	26·9379	26·9652	26·9926	27·0199	27·0473	27·0747	27·1021	27·1296	27·1570
1980	27·1844	27·2119	27·2394	27·2669	27·2944	27·3219	27·3494	27·3770	27·4046	27·4321
1990	27·4597	27·4873	27·5150	27·5426	27·5702	27·5979	27·6256	27·6533	27·6810	27·7087
2000	27·7364	27·7641	27·7919	27·8197	27·8475	27·8753	27·9031	27·9309	27·9587	27·9866
2010	28·0145	28·0423	28·0702	28·0981	28·1261	28·1540	28·1820	28·2099	28·2379	28·2659
2020	28·2939	28·3219	28·3500	28·3780	28·4061	28·4341	28·4622	28·4903	28·5185	28·5466
2030	28·5747	28·6029	28·6311	28·6593	28·6875	28·7157	28·7439	28·7721	28·8004	28·8287
2040	28·8570	28·8852	28·9136	28·9419	28·9702	28·9986	29·0269	29·0553	29·0837	29·1121
2050	29·1406	29·1690	29·1974	29·2259	29·2544	29·2829	29·3114	29·3399	29·3684	29·3970
2060	29·4255	29·4541	29·4827	29·5113	29·5399	29·5686	29·5972	29·6259	29·6545	29·6832
2070	29·7119	29·7406	29·7694	29·7981	29·8269	29·8556	29·8844	29·9132	29·9420	29·9709
2080	29·9997	30·0285	30·0574	30·0863	30·1152	30·1441	30·1730	30·2020	30·2309	30·2599
2090	30·2888	30·3178	30·3468	30·3759	30·4049	30·4339	30·4630	30·4921	30·5212	30·5503
2100	30·5794	30·6085	30·6377	30·6668	30·6960	30·7251	30·7544	30·7836	30·8128	30·8421
2110	30·8713	30·9006	30·9299	30·9591	30·9885	31·0178	31·0471	31·0765	31·1058	31·1352
2120	31·1646	31·1940	31·2234	31·2529	31·2823	31·3118	31·3413	31·3708	31·4003	31·4298
2130	31·4593	31·4889	31·5184	31·5480	31·5776	31·6072	31·6368	31·6664	31·6961	31·7257
2140	31·7554	31·7851	31·8148	31·8445	31·8742	31·9040	31·9337	31·9635	31·9933	32·0231
2150	32·0529	32·0827	32·1125	32·1424	32·1723	32·2021	32·2320	32·2619	32·2919	32·3218
2160	32·3517	32·3817	32·4117	32·4417	32·4717	32·5017	32·5317	32·5617	32·5918	32·6218
2170	32·6520	32·6821	32·7122	32·7423	32·7725	32·8026	32·8328	32·8630	32·8932	32·9234
2180	32·9536	32·9839	33·0141	33·0444	33·0747	33·1050	33·1353	33·1656	33·1959	33·2263
2190	33·2566	33·2870	33·3174	33·3478	33·3782	33·4087	33·4391	33·4696	33·5001	33·5305
2200	33·5610	33·5916	33·6221	33·6526	33·6832	33·7138	33·7444	33·7750	33·8056	33·8362
		1	2	3	4	5	6	7	8	9

Table of energies—continued.

Velocity.		1	2	3	4	5	6	7	8	9
2200	33·5610	33·5916	33·6221	33·6526	33·6832	33·7138	33·7444	33·7750	33·8056	33·8362
2210	33·8668	33·8975	33·9282	33·9588	33·9895	34·0203	34·0510	34·0817	34·1125	34·1432
2220	34·1740	34·2048	34·2356	34·2664	34·2973	34·3281	34·3590	34·3899	34·4208	34·4517
2230	34·4826	34·5135	34·5445	34·5754	34·6064	34·6374	34·6684	34·6994	34·7304	34·7615
2240	34·7925	34·8236	34·8547	34·8858	34·9169	34·9480	34·9792	35·0103	35·0415	35·0727
2250	35·1039	35·1351	35·1663	35·1976	35·2288	35·2601	35·2914	35·3226	35·3540	35·3853
2260	35·4166	35·4480	35·4793	35·5107	35·5421	35·5735	35·6049	35·6363	35·6678	35·6993
2270	35·7307	35·7622	35·7937	35·8252	35·8568	35·8883	35·9199	35·9514	35·9830	36·0146
2280	36·0462	36·0779	36·1095	36·1411	36·1728	36·2045	36·2362	36·2679	36·2996	36·3314
2290	36·3631	36·3949	36·4267	36·4585	36·4903	36·5221	36·5539	36·5858	36·6176	36·6495
2300	36·6814	36·7133	36·7452	36·7771	36·8091	36·8410	36·8730	36·9050	36·9370	36·9690
2310	37·0010	37·0331	37·0651	37·0972	37·1293	37·1614	37·1935	37·2256	37·2578	37·2899
2320	37·3221	37·3543	37·3865	37·4187	37·4509	37·4831	37·5154	37·5477	37·5799	37·6122
2330	37·6445	37·6769	37·7092	37·7415	37·7739	37·8063	37·8387	37·8711	37·9035	37·9359
2340	37·9684	38·0008	38·0333	38·0658	38·0983	38·1308	38·1633	38·1959	38·2284	38·2610
2350	38·2936	38·3261	38·3588	38·3914	38·4240	38·4567	38·4894	38·5220	38·5547	38·5874
2360	38·6202	38·6529	38·6856	38·7184	38·7512	38·7840	38·8168	38·8496	38·8824	38·9153
2370	38·9481	38·9810	39·0139	39·0468	39·0797	39·1127	39·1456	39·1786	39·2115	39·2445
2380	39·2775	39·3105	39·3436	39·3766	39·4097	39·4427	39·4758	39·5089	39·5420	39·5751
2390	39·6083	39·6414	39·6746	39·7078	39·7410	39·7742	39·8074	39·8406	39·8739	39·9071
2400	39·9404	39·9737	40·0070	40·0403	40·0737	40·1070	40·1404	40·1737	40·2071	40·2405
2410	40·2739	40·3074	40·3408	40·3743	40·4077	40·4412	40·4747	40·5082	40·5418	40·5753
2420	40·6089	40·6424	40·6760	40·7096	40·7432	40·7768	40·8105	40·8441	40·8778	40·9115
2430	40·9452	40·9789	41·0126	41·0463	41·0801	41·1138	41·1476	41·1814	41·2152	41·2490
2440	41·2829	41·3167	41·3506	41·3844	41·4183	41·4522	41·4861	41·5201	41·5540	41·5880
2450	41·6219	41·6559	41·6899	41·7239	41·7580	41·7920	41·8260	41·8601	41·8942	41·9283
2460	41·9624	41·9965	42·0307	42·0648	42·0990	42·1332	42·1673	42·2015	42·2358	42·2700
2470	42·3043	42·3385	42·3728	42·4071	42·4414	42·4757	42·5100	42·5444	42·5787	42·6131
2480	42·6475	42·6819	42·7161	42·7507	42·7852	42·8196	42·8541	42·8886	42·9231	42·9576
2490	42·9921	43·0267	43·0612	43·0958	43·1304	43·1649	43·1996	43·2342	43·2688	43·3035
2500	43·3381	43·3728	43·4075	43·4422	43·4769	43·5117	43·5464	43·5812	43·6159	43·6507
2510	43·6855	43·7203	43·7552	43·7900	43·8249	43·8597	43·8946	43·9295	43·9644	43·9993
2520	44·0343	44·0693	44·1042	44·1392	44·1742	44·2092	44·2442	44·2793	44·3143	44·3494
2530	44·3845	44·4196	44·4547	44·4898	44·5249	44·5600	44·5952	44·6304	44·6656	44·7008
2540	44·7360	44·7713	44·8065	44·8418	44·8771	44·9123	44·9476	44·9830	45·0183	45·0536
2550	45·0890	45·1244	45·1597	45·1951	45·2306	45·2656	45·3014	45·3369	45·3723	45·4078
2560	45·4433	45·4788	45·5144	45·5499	45·5854	45·6210	45·6566	45·6922	45·7278	45·7634
2570	45·7990	45·8347	45·8703	45·9060	45·9417	45·9774	46·0131	46·0489	46·0846	46·1204
2580	46·1561	46·1919	46·2277	46·2635	46·2994	46·3352	46·3711	46·4069	46·4428	46·4787
2590	46·5146	46·5505	46·5865	46·6225	46·6584	46·6944	46·7304	46·7664	46·8024	46·8384
2600	46·8745	46·9106	46·9467	46·9828	47·0189	47·0550	47·0911	47·1273	47·1634	47·1996
2610	47·2358	47·2720	47·3082	47·3444	47·3807	47·4169	47·4532	47·4895	47·5258	47·5621
2620	47·5984	47·6348	47·6711	47·7075	47·7439	47·7803	47·8167	47·8531	47·8896	47·9260
2630	47·9625	47·9990	48·0355	48·0720	48·1085	48·1450	48·1816	48·2181	48·2547	48·2913
2640	48·3279	48·3645	48·4011	48·4378	48·4745	48·5111	48·5478	48·5845	48·6212	48·6580
		·1	2	3	4	5	6	7	8	9

Table of energies—continued.

Velocity.		1	2	3	4	5	6	7	8	9
2640	48·3279	48·3645	48·4011	48·4378	48·4745	48·5111	48·5478	48·5845	48·6212	48·6580
2650	48·6947	48·7315	48·7682	48·8050	48·8418	48·8786	48·9155	48·9523	48·9892	49·0260
2660	49·0629	49·0998	49·1367	49·1736	49·2106	49·2475	49·2845	49·3215	49·3585	49·3955
2670	49·4325	49·4695	49·5066	49·5437	49·5807	49·6178	49·6549	49·6920	49·7292	49·7663
2680	49·8035	49·8407	49·8778	49·9150	49·9523	49·9895	50·0267	50·0640	50·1013	50·1385
2690	50·1758	50·2132	50·2505	50·2878	50·3252	50·3625	50·3999	50·4373	50·4747	50·5122
2700	50·5496	50·5870	50·6245	50·6620	50·6995	50·7370	50·7745	50·8120	50·8496	50·8871
2710	50·9247	50·9623	50·9999	51·0375	51·0752	51·1128	51·1505	51·1881	51·2258	51·2635
2720	51·3012	51·3390	51·3767	51·4145	51·4522	51·4900	51·5278	51·5656	51·6035	51·6413
2730	51·6792	51·7170	51·7549	51·7928	51·8307	51·8686	51·9066	51·9445	51·9825	52·0205
2740	52·0584	52·0965	52·1345	52·1725	52·2106	52·2486	52·2867	52·3248	52·3629	52·4010
2750	52·4391	52·4773	52·5154	52·5536	52·5918	52·6300	52·6682	52·7064	52·7447	52·7829
2760	52·8212	52·8595	52·8978	52·9361	52·9744	53·0128	53·0511	53·0895	53·1279	53·1662
2770	53·2047	53·2431	53·2815	53·3200	53·3584	53·3969	53·4354	53·4739	53·5124	53·5510
2780	53·5895	53·6281	53·6666	53·7052	53·7438	53·7824	53·8211	53·8597	53·8984	53·9370
2790	53·9757	54·0144	54·0531	54·0919	54·1306	54·1694	54·2081	54·2469	54·2857	54·3245
2800	54·3633	54·4022	54·4410	54·4799	54·5188	54·5577	54·5966	54·6355	54·6744	54·7134
2810	54·7523	54·7913	54·8303	54·8693	54·9083	54·9474	54·9864	55·0255	55·0645	55·1036
2820	55·1427	55·1819	55·2210	55·2601	55·2993	55·3385	55·3776	55·4168	55·4560	55·4953
2830	55·5345	55·5738	55·6130	55·6523	55·6916	55·7309	55·7702	55·8096	55·8489	55·8883
2840	55·9277	55·9670	56·0065	56·0459	56·0853	56·1248	56·1642	56·2037	56·2432	56·2827
2850	56·3222	56·3618	56·4013	56·4409	56·4804	56·5200	56·5596	56·5992	56·6389	56·6785
2860	56·7182	56·7578	56·7975	56·8372	56·8769	56·9167	56·9564	56·9961	57·0359	57·0757
2870	57·1155	57·1553	57·1951	57·2350	57·2748	57·3147	57·3545	57·3944	57·4343	57·4743
2880	57·5142	57·5541	57·5941	57·6341	57·6741	57·7141	57·7541	57·7941	57·8342	57·8742
2890	57·9143	57·9544	57·9945	58·0346	58·0747	58·1148	58·1550	58·1952	58·2354	58·2756
2900	58·3158	58·3560	58·3962	58·4365	58·4768	58·5170	58·5573	58·5976	58·6380	58·6783
2910	58·7187	58·7590	58·7994	58·8398	58·8802	58·9206	58·9610	59·0015	59·0419	59·0824
2920	59·1229	59·1624	59·2029	59·2435	59·2840	59·3246	59·3651	59·4067	59·4473	59·4879
2930	59·5286	59·5692	59·6099	59·6505	59·6912	59·7319	59·7726	59·8133	59·8541	59·8948
2940	59·9356	59·9764	60·0172	60·0580	60·0988	60·1396	60·1805	60·2213	60·2622	60·3031
2950	60·3440	60·3849	60·4259	60·4668	60·5078	60·5487	60·5897	60·6307	60·6717	60·7128
2960	60·7538	60·7949	60·8359	60·8770	60·9181	60·9592	61·0004	61·0415	61·0827	61·1238
2970	61·1650	61·2062	61·2474	61·2886	61·3299	61·3711	61·4124	61·4537	61·4950	61·5363
2980	61·5776	61·6189	61·6603	61·7016	61·7430	61·7844	61·8258	61·8672	61·9086	61·9501
2990	61·9915	62·0330	62·0745	62·1160	62·1575	62·1991	62·2406	62·2822	62·3237	62·3653
3000	62·4069	62·4486	62·4902	62·5318	62·5734	62·6151	62·6568	62·6985	62·7402	62·7818
		1	2	3	4	5	6	7	8	9

Table giving in dinamodes the energy stored up in 1 *kilogramme in weight, moving at any velocity between* 1 *and* 1000 *metres per second.*

Velocity.		1	2	3	4	5	6	7	8	9
	·00000	·00005	·00020	·00045	·00082	·00127	·00183	·00249	·00326	·00413
10	·00510	·00617	·00734	·00861	·00999	·01147	·01305	·01473	·01651	·01840
20	·02038	·02247	·02466	·02696	·02935	·03185	·03445	·03715	·03995	·04285
30	·04586	·04897	·05218	·05549	·05891	·06243	·06604	·06976	·07359	·07756
40	·08154	·08566	·08989	·09422	·09866	·10319	·10783	·11257	·11741	·12235
50	·12740	·13255	·13780	·14315	·14860	·15415	·15981	·16557	·17143	·17739
60	·18346	·18962	·19589	·20226	·20873	·21531	·22188	·22876	·23564	·24262
70	·24970	·25689	·26418	·27157	·27906	·28665	·29434	·30214	·31004	·31804
80	·32614	·33435	·34265	·35106	·35957	·36819	·37690	·38572	·39463	·40365
90	·41278	·42200	·43132	·44075	·45028	·45991	·46965	·47948	·48942	·49946
100	·50960	·51984	·53019	·54063	·55118	·56183	·57258	·58344	·59440	·60546
110	·61662	·62788	·63924	·65071	·66228	·67395	·68572	·69789	·70957	·72164
120	·73382	·74610	·75849	·77097	·78356	·79625	·80904	·82193	·83493	·84802
130	·86122	·87452	·88793	·90143	·91504	·92875	·94256	·95647	·97048	·98460
140	·99881	1·01314	1·02756	1·04208	1·05671	1·07143	1·08626	1·10129	1·11623	1·13136
150	1·14660	1·16194	1·17738	1·19292	1·20857	1·22431	1·24016	1·25611	1·27216	1·28832
160	1·30458	1·32093	1·33740	1·35396	1·37062	1·38739	1·40425	1·42122	1·43829	1·45547
170	1·47274	1·49012	1·50760	1·52518	1·54286	1·56065	1·57854	1·59652	1·61461	1·63281
180	1·65110	1·66950	1·68880	1·70660	1·72530	1·74410	1·76301	1·78201	1·80113	1·82034
190	1·83965	1·85907	1·87859	1·89821	1·91793	1·93775	1·95768	1·97771	1·99783	2·01807
200	2·03840	2·05883	2·07937	2·10001	2·12075	2·14159	2·16254	2·18358	2·20473	2·22598
210	2·24734	2·26879	2·29035	2·31200	2·33376	2·35563	2·37759	2·39965	2·42182	2·44409
220	2·46646	2·48894	2·51151	2·53419	2·55697	2·57985	2·60283	2·62592	2·64910	2·67239
230	2·69578	2·71928	2·74287	2·76657	2·79036	2·81427	2·83827	2·86237	2·88658	2·91089
240	2·93530	2·95980	2·98442	3·00913	3·03395	3·05887	3·08389	3·10902	3·13424	3·15957
250	3·18500	3·21053	3·23616	3·26190	3·28773	3·31367	3·33971	3·36586	3·39210	3·41845
260	3·44490	3·47145	3·48810	3·51485	3·54170	3·57867	3·60572	3·63288	3·66015	3·68752
270	3·71498	3·74255	3·77022	3·79800	3·82587	3·85385	3·88192	3·91010	3·93839	3·96678
280	3·99526	4·02385	4·05254	4·08133	4·11023	4·13923	4·16832	4·19752	4·22683	4·25623
290	4·28574	4·31534	4·34505	4·37486	4·40478	4·43480	4·46491	4·49513	4·52545	4·55587
300	4·58640	4·61703	4·64775	4·67859	4·70952	4·74055	4·77169	4·80293	4·83426	4·86571
310	4·89726	4·92890	4·99065	4·99250	5·02445	5·05650	5·08866	5·12092	5·15328	5·18574
320	5·21830	5·25097	5·28374	5·31660	5·34958	5·38265	5·41582	5·44910	5·48248	5·51596
330	5·54954	5·58322	5·61701	5·65090	5·68489	5·71899	5·75318	5·78748	5·82187	5·85637
340	5·89098	5·92568	5·96048	5·99539	6·03040	6·06551	6·10073	6·13604	6·17146	6·20698
350	6·24260	6·27832	6·31415	6·35007	6·38610	6·42223	6·45847	6·49480	6·53124	6·56777
360	6·60442	6·64116	6·67800	6·71495	6·75200	6·78915	6·82640	6·86375	6·90120	6·93876
370	6·97642	7·01418	7·05205	7·09001	7·12808	7·16625	7·20452	7·24289	7·28137	7·31994
380	7·35862	7·39740	7·43629	7·47526	7·51435	7·55354	7·59283	7·63223	7·67172	7·71132
390	7·75101	7·79081	7·83073	7·87072	7·91083	7·95103	7·99134	8·03175	8·07226	8·11288
400	8·15360	8·19442	8·23534	8·27636	8·31749	8·35871	8·40004	8·44147	8·48300	8·52463
410	8·56639	8·60822	8·65016	8·69221	8·73435	8·77660	8·81894	8·86139	8·90394	8·94660
420	8·98935	9·03221	9·07517	9·11823	9·16139	9·20466	9·24803	9·29149	9·33506	9·37873
430	9·42251	9·46639	9·51037	9·55445	9·59863	9·64292	9·68730	9·73178	9·77637	9·82106
440	9·86585	9·91075	9·95575	10·00084	10·03605	10·08135	10·13676	10·18227	10·22787	10·27359
		1	2	3	4	5	6	7	8	9

Table giving in dinamodes the energy stored up in 1 *kilogramme in weight, etc.*—continued.

Velocity.		1	2	3	4	5	6	7	8	9
440	9·86585	9·91075	9·95575	10·00084	10·03605	10·08135	10·13676	10·18227	10·22787	10·27359
450	10·31940	10·36531	10·41133	10·45745	10·50367	10·54999	10·59642	10·64294	10·68957	10·73630
460	10·78313	10·83007	10·87710	10·92424	10·97148	11·01883	11·06627	11·11381	11·16146	11·20921
470	11·25706	11·30502	11·35307	11·40123	11·44949	11·49785	11·54631	11·59488	11·64355	11·69232
480	11·74119	11·79016	11·83924	11·88842	11·93769	11·98708	12·03656	12·08614	12·13583	12·18562
490	12·23550	12·28550	12·33558	12·38578	12·43607	12·48647	12·53697	12·58758	12·63828	12·68909
500	12·74000	12·79101	12·84212	12·89334	12·94465	12·99607	13·04759	13·09922	13·15094	13·20277
510	13·25470	13·30673	13·35891	13·41114	13·46348	13·51592	13·55845	13·61109	13·66383	13·71668
520	13·77964	13·83269	13·88584	13·93909	13·99245	14·04590	14·09946	14·15312	14·20689	14·26075
530	14·31472	14·36879	14·42296	14·47723	14·53160	14·58608	14·64066	14·69534	14·75012	14·80500
540	14·86000	14·91508	14·97027	15·02556	15·08096	15·13645	15·19205	15·24775	15·30355	15·35945
550	15·41546	15·47157	15·52778	15·58409	15·64040	15·69701	15·75363	15·81035	15·86717	15·92409
560	15·98112	16·03824	16·09547	16·15280	16·21023	16·26777	16·32540	16·38314	16·44098	16·49892
570	16·55697	16·61511	16·67336	16·73171	16·79016	16·84872	16·90737	16·96613	17·02499	17·08395
580	17·14301	17·20218	17·26144	17·32081	17·38028	17·43985	17·49953	17·55930	17·61918	17·67916
590	17·73924	17·79942	17·85971	17·92010	17·98059	18·04118	18·10188	18·16267	18·22357	18·28457
600	18·34567	18·40687	18·46818	18·52958	18·59109	18·65271	18·71442	18·77623	18·83815	18·90017
610	18·96220	19·02451	19·08683	19·14926	19·21179	19·27442	19·33715	19·39999	19·46292	19·52596
620	19·58911	19·65235	19·71569	19·77914	19·84269	19·90634	19·97009	20·03394	20·09790	20·16195
630	20·22611	20·29036	20·35473	20·41919	20·48376	20·54843	20·61320	20·67807	20·74304	20·80812
640	20·87330	20·93858	21·00396	21·06944	21·13503	21·20072	21·26651	21·33240	21·39821	21·46441
650	21·53071	21·59710	21·66351	21·73001	21·79641	21·86322	21·93003	21·99694	22·06395	22·13107
660	22·19828	22·26560	22·33300	22·40053	22·46815	22·53590	22·60372	22·67165	22·73969	22·80782
670	22·87605	22·95439	23·02283	23·09137	23·15001	23·21876	23·28761	23·35656	23·42561	23·49476
680	23·56402	23·63338	23·70283	23·77240	23·84206	23·91182	23·98169	24·05166	24·12173	24·19190
690	24·26217	24·33255	24·40303	24·47361	24·54429	24·61507	24·68596	24·75695	24·82804	24·89923
700	24·97052	25·04192	25·11341	25·18501	25·25671	25·32852	25·40042	25·47243	25·54454	25·61675
710	25·68906	25·76148	25·83399	25·90661	25·97933	26·05215	26·12508	26·19810	26·27123	26·34446
720	26·41779	26·49123	26·56476	26·63840	26·71214	26·78598	26·85992	26·93397	27·00812	27·08237
730	27·15672	27·23117	27·30572	27·38038	27·45514	27·53000	27·60496	27·68003	27·75519	27·83046
740	27·90583	27·98130	28·05688	28·13255	28·20833	28·28421	28·36019	28·43628	28·51246	28·58875
750	28·66514	28·74163	28·81822	28·89492	28·97172	29·04862	29·12562	29·20272	29·27992	29·35723
760	29·43464	29·51215	29·58976	29·66748	29·74529	29·82321	29·90123	29·97935	30·05758	30·13590
770	30·21433	30·29286	30·37149	30·45023	30·52906	30·60800	30·68704	30·76618	30·84542	30·92477
780	31·00422	31·08376	31·16342	31·24317	31·32302	31·40298	31·48304	31·56320	31·64346	31·72382
790	31·80429	31·88486	31·96553	32·04630	32·12718	32·20815	32·28923	32·37041	32·45169	32·53307
800	32·61456	32·69615	32·77784	32·85963	32·94152	33·02352	33·10561	33·18781	33·27011	33·35251
810	33·43502	33·51763	33·60034	33·68315	33·76606	33·84907	33·93219	34·01541	34·09873	34·18215
820	34·26567	34·34929	34·43303	34·51685	34·60079	34·68482	34·76896	34·85319	34·93753	35·02197
830	35·10652	35·19116	35·27591	35·36076	35·44571	35·53076	35·61591	35·70117	35·78653	35·87199
840	35·95755	36·04322	36·12898	36·21485	36·30082	36·38689	36·47307	36·55934	36·64572	36·73220
850	36·81878	36·90546	36·99225	37·07914	37·16613	37·25322	37·34041	37·42770	37·51510	37·60260
860	37·69020	37·77790	37·86571	37·95361	38·14162	38·12973	38·21794	38·30626	38·39467	38·48319
870	38·57181	38·66053	38·74936	38·83828	38·92731	39·01644	39·10567	39·19501	39·28444	39·37398
880	39·46362	39·55336	39·64320	39·73315	39·82319	39·91334	40·00359	40·09394	40·18440	40·27495
		1	2	3	4	5	6	7	8	9

Table giving in dinamodes the energy stored up in 1 *kilogramme in weight, etc.*—continued.

Velocity.		1	2	3	4	5	6	7	8	9
880	39·46362	39·55336	39·64320	39·73315	39·82319	39·91334	40·00359	40·09394	40·18440	40·27495
890	40·36561	40·45637	40·54723	40·63820	40·72927	40·82043	40·91170	41·00308	41·09455	41·18612
900	41·27780	41·36958	41·46146	41·55345	41·64553	41·73772	41·83001	41·92240	42·01489	42·10749
910	42·20018	42·29298	42·38588	42·47888	42·57199	42·66520	42·75850	42·85191	42·94542	43·03904
920	43·13275	43·22657	43·32049	43·41451	43·50864	43·60286	43·69719	43·79162	43·88615	43·98078
930	44·07552	44·17035	44·26530	44·36034	44·45548	44·55072	44·64607	44·74152	44·83707	44·93272
940	45·02848	45·12433	45·22029	45·31635	45·41251	45·50878	45·60514	45·70161	45·79818	45·89485
950	45·99162	46·08850	46·18548	46·28256	46·37974	46·47702	46·57441	46·67189	46·76948	46·86717
960	46·96497	47·06286	47·16086	47·25896	47·35716	47·45546	47·55386	47·65237	47·75098	47·84969
970	47·94850	48·04741	48·14643	48·24555	48·34477	48·44409	48·54351	48·64304	48·74266	48·84239
980	48·94222	49·04216	49·14219	49·24233	49·34257	49·44291	49·54335	49·64389	49·74454	49·84529
990	49·94614	50·04709	50·14815	50·24930	50·35056	50·45192	50·55338	50·65495	50·75661	50·85838
1000	50·96025	51·06222	51·16429	51·26647	51·36875	51·47113	51·57361	51·67619	51·77888	51·88166
		1	2	3	4	5	6	7	8	9

Table showing the work in dinamodes that 1 *kilogramme of gunpowder is capable of performing in expanding from volume* = 1, *to any given number of volumes up to* 40.

Volumes.	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09
1·0	·000	·667	1·319	1·956	2·578	3·187	3·782	4·365	4·934	5·492
·1	6·038	6·574	7·098	7·612	8·117	8·612	9·098	9·576	10·044	10·505
·2	10·957	11·402	11·841	12·273	12·697	13·114	13·525	13·929	14·327	14·718
·3	15·104	15·483	15·858	16·227	16·591	16·951	17·305	17·655	18·000	18·340
·4	18·676	19·009	19·337	19·661	19·980	20·030	20·608	20·916	21·220	21·521
·5	21·818	22·112	22·403	22·690	22·974	23·256	23·533	23·808	24·080	24·348
·6	24·615	24·879	25·140	25·397	25·653	25·906	26·157	26·404	26·630	26·893
·7	27·133	27·372	27·608	27·842	28·073	28·303	28·531	28·757	28·981	29·202
·8	29·422	29·639	29·856	30·070	30·282	30·493	30·702	30·909	31·114	31·318
·9	31·520	31·764	31·920	32·118	32·313	32·508	32·701	32·892	33·083	33·271
2·0	33·458	33·643	33·826	34·008	34·189	34·367	34·545	34·721	34·897	35·073
·1	35·247	35·420	35·592	35·763	35·932	36·100	36·267	36·432	36·597	36·761
·2	36·924	37·086	37·248	37·407	37·566	37·724	37·881	38·036	38·191	38·345
·3	38·498	38·650	38·801	38·951	39·100	39·248	39·396	39·542	39·688	39·832
·4	39·998	40·118	40·260	40·401	40·542	40·681	40·819	40·957	41·094	41·230
·5	41·365	41·499	41·633	41·766	41·899	42·029	42·160	42·289	42·418	42·547
·6	42·675	42·803	42·930	43·056	43·181	43·305	43·428	43·552	43·675	43·797
·7	43·918	44·039	44·159	44·278	44·398	44·516	44·634	44·752	44·868	44·985
·8	45·101	45·216	45·331	45·445	45·558	45·571	45·784	45·896	46·007	46·117
·9	46·228	46·338	46·447	46·555	46·664	46·772	46·879	46·986	47·024	47·130
3·0	47·303	47·408	47·512	47·616	47·720	47·823	47·925	48·027	48·129	48·230
·1	48·351	48·431	48·531	48·631	48·730	48·830	48·928	49·027	49·124	49·221
·2	49·318	49·414	49·510	49·606	49·701	49·796	49·891	49·985	50·079	50·173
·3	50·265	50·358	50·451	50·543	50·634	50·726	50·817	50·907	50·998	51·088
·4	51·177	51·267	51·356	51·445	51·533	51·621	51·708	51·795	51·883	51·969
·5	52·056	52·142	52·227	52·313	52·398	52·482	52·567	52·651	52·735	52·818
·6	52·900	52·983	53·066	53·148	53·230	53·312	53·393	53·474	53·555	53·636
·7	53·716	53·796	53·876	53·956	54·035	54·114	54·192	54·271	54·349	54·427
·8	54·505	54·583	54·660	54·737	54·813	54·889	54·966	55·041	55·117	55·193
·9	55·268	55·343	55·418	55·492	55·567	55·640	55·714	55·788	55·861	55·934
4·0	56·007	56·079	56·151	56·224	56·295	56·367	56·439	56·510	56·581	56·652
·1	56·723	56·793	56·864	56·934	57·003	57·073	57·143	57·211	57·280	57·349
·2	57·418	57·486	57·554	57·623	57·690	57·758	57·825	57·892	57·960	58·027
·3	58·093	58·160	58·226	58·292	58·358	58·423	58·489	58·554	58·620	58·685
·4	58·750	58·814	58·878	58·942	59·007	59·071	59·134	59·198	59·261	59·324
·5	59·388	59·451	59·514	59·576	59·659	59·701	59·763	59·825	59·887	59·948
·6	60·001	60·071	60·132	60·192	60·253	60·314	60·374	60·434	60·494	60·554
·7	60·614	60·673	60·732	60·792	60·851	60·910	60·969	61·027	61·086	61·144
·8	61·203	61·261	61·318	61·376	61·434	61·491	61·548	61·606	61·663	61·720
·9	61·776	61·833	61·889	61·946	62·002	62·058	62·114	62·170	62·225	62·280
5·0	62·335	62·391	62·446	62·501	62·556	62·610	62·665	62·720	62·774	62·828
·1	62·882	62·936	62·990	63·043	63·097	63·150	63·203	63·256	63·310	63·363
·2	63·415	63·468	63·520	63·573	63·625	63·677	63·729	63·781	63·833	63·885
·3	63·936	63·988	64·039	64·090	64·141	64·192	64·243	64·294	64·345	64·395
·4	64·446	64·496	64·547	64·597	64·647	64·697	64·747	64·797	64·846	64·896
	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09

Table showing the work in dinamodes that 1 *kilogramme of gunpowder, etc.*—continued.

Volumes.	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09
5·5	64·944	64·994	65·043	65·092	65·141	65·190	65·239	65·287	65·335	65·384
·6	65·432	65·481	65·529	65·576	65·624	65·672	65·720	65·767	65·815	65·863
·7	65·910	65·957	66·004	66·051	66·098	66·145	66·192	66·238	66·284	66·331
·8	66·379	66·423	66·470	66·516	66·561	66·607	66·653	66·698	66·744	66·790
·9	66·835	66·880	66·925	66·970	67·015	67·060	67·105	67·150	67·194	67·239
6·0	67·283	67·327	67·372	67·416	67·460	67·504	67·548	67·591	67·635	67·679
·1	67·722	67·766	67·810	67·853	67·896	67·939	67·982	68·025	68·068	68·111
·2	68·154	68·197	68·240	68·282	68·325	68·367	68·409	68·451	68·494	68·536
·3	68·578	68·620	68·661	68·704	68·745	68·787	68·829	68·870	68·911	68·952
·4	68·993	69·034	69·075	69·116	69·157	69·198	69·239	69·280	69·320	69·361
·5	69·402	69·442	69·482	69·522	69·563	69·603	69·643	69·683	69·724	69·764
·6	69·803	69·843	69·883	69·922	69·962	70·001	70·041	70·080	70·120	70·159
·7	70·198	70·237	70·276	70·315	70·354	70·393	70·432	70·470	70·509	70·548
·8	70·586	70·624	70·662	70·700	70·739	70·777	70·815	70·853	70·891	70·929
·9	70·966	71·004	71·041	71·079	71·116	71·153	71·191	71·229	71·267	71·303
7·0	71·340	71·377	71·414	71·451	71·488	71·524	71·562	71·598	71·635	71·672
·1	71·708	71·744	71·780	71·816	71·852	71·899	71·925	71·961	71·997	72·033
·2	72·069	72·106	72·141	72·177	72·212	72·247	72·283	72·318	72·354	72·389
·3	72·425	72·460	72·496	72·531	72·565	72·600	72·635	72·670	72·705	72·739
·4	72·774	72·809	72·844	72·878	72·913	72·947	72·981	73·016	73·050	73·084
·5	73·118	73·152	73·186	73·220	73·254	73·288	73·323	73·356	73·390	73·423
·6	73·456	73·490	73·523	73·557	73·590	73·623	73·657	73·690	73·724	73·757
·7	73·790	73·823	73·856	73·889	73·922	73·955	73·988	74·020	74·053	74·086
·8	74·119	74·151	74·184	74·217	74·496	74·282	74·314	74·346	74·378	74·410
·9	74·442	74·474	74·506	74·538	74·570	74·602	74·634	74·666	74·698	74·729
8·0	74·760	74·792	74·823	74·855	74·886	74·917	74·949	74·980	75·011	75·043
·1	75·074	75·106	75·137	75·168	75·200	75·230	75·261	75·292	75·322	75·353
·2	75·384	75·415	75·445	75·476	75·511	75·537	75·568	75·599	75·629	75·660
·3	75·690	75·720	75·750	75·781	75·811	75·841	75·871	75·901	75·931	75·961
·4	75·991	76·021	76·051	76·081	76·111	76·141	76·171	76·200	76·230	76·260
·5	76·288	76·318	76·347	76·376	76·406	76·435	76·464	76·494	76·523	76·552
·6	76·582	76·611	76·640	76·670	76·700	76·729	76·757	76·785	76·814	76·843
·7	76·872	76·900	76·929	76·958	76·986	77·015	77·043	77·071	77·101	77·129
·8	77·157	77·186	77·214	77·243	77·271	77·299	77·327	77·356	77·384	77·412
·9	77·440	77·468	77·496	77·524	77·552	77·580	77·608	77·636	77·664	77·692
9·0	77·719	77·747	77·774	77·802	77·829	77·857	77·884	77·912	77·940	77·967
·1	77·994	78·022	78·049	78·076	78·103	78·131	78·158	78·185	78·212	78·239
·2	78·266	78·293	78·320	78·347	78·374	78·401	78·428	78·455	78·481	78·508
·3	78·535	78·561	78·588	78·614	78·641	78·668	78·694	78·720	78·747	78·773
·4	78·799	78·825	78·852	78·878	78·904	78·930	78·957	78·983	79·009	79·035
·5	79·061	79·087	79·113	79·139	79·165	79·191	79·217	79·243	79·269	79·295
·6	79·320	79·346	79·371	79·397	79·422	79·448	79·473	79·499	79·524	79·550
·7	79·576	79·601	79·626	79·651	79·676	79·702	79·727	79·752	79·777	79·803
·8	79·828	79·853	79·878	79·904	79·928	79·953	79·978	80·003	80·034	80·053
·9	80·078	80·103	80·127	80·153	80·177	80·202	80·226	80·251	80·275	80·300
	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09

Table showing the work in dinamodes that 1 *kilogramme of gunpowder, etc.*—continued.

Volumes.	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09
10·0	80·324	80·568	80·809	81·048	81·284	81·518	81·749	81·977	82·204	82·427
11	82·649	82·868	83·085	83·299	83·513	83·723	83·932	84·138	84·342	84·545
12	84·746	84·945	85·142	85·338	85·531	85·723	85·912	86·100	86·293	86·477
13	86·654	86·835	87·015	87·194	87·371	87·548	87·722	87·895	88·066	88·236
14	88·404	88·571	88·736	88·901	89·065	89·228	89·389	89·550	89·708	89·865
15	90·020	90·173	90·326	90·478	90·629	90·779	90·928	91·077	91·225	91·372
16	91·519	91·665	91·809	91·952	92·095	92·235	92·374	92·512	92·648	92·783
17	92·917	93·053	93·183	93·316	93·447	93·578	93·709	93·839	93·969	94·098
18	94·227	94·355	94·483	94·609	94·734	94·858	94·981	95·102	95·222	95·341
19	95·459	95·577	95·694	95·811	95·928	96·045	96·161	96·277	96·392	96·506
20	96·620	96·734	96·846	96·957	97·067	97·177	97·286	97·395	97·503	97·611
21	97·719	97·826	97·933	98·039	98·144	98·248	98·352	98·456	98·559	98·661
22	98·763	98·865	98·966	99·066	99·167	99·266	99·365	99·463	99·561	99·658
23	99·755	99·851	99·947	100·043	100·137	100·232	100·326	100·420	100·514	100·607
24	100·701	100·794	100·886	100·978	101·069	101·160	101·251	101·341	101·431	101·520
25	101·609	101·697	101·785	101·873	101·961	102·047	102·134	102·220	102·306	102·391
26	102·476	102·561	102·646	102·729	102·813	102·897	102·980	103·062	103·145	103·227
27	103·309	103·390	103·471	103·551	103·632	103·712	103·792	103·871	103·950	104·028
28	104·107	104·184	104·262	104·339	104·416	104·493	104·563	104·645	104·721	104·796
29	104·871	104·946	105·020	105·094	105·167	105·241	105·315	105·388	105·461	105·533
30	105·605	105·678	105·749	105·821	105·892	105·963	106·034	106·104	106·174	106·244
31	106·313	106·383	106·452	106·521	106·590	106·658	106·725	106·793	106·860	106·928
32	106·995	107·062	107·128	107·195	107·261	107·328	107·394	107·459	107·525	107·590
33	107·655	107·741	107·785	107·849	107·913	107·977	108·041	108·105	108·175	108·238
34	108·301	108·364	108·427	108·489	108·551	108·613	108·675	108·736	108·798	108·859
35	108·920	108·980	109·041	109·101	109·161	109·221	109·281	109·340	109·400	109·460
36	109·519	109·578	109·637	109·695	109·754	109·813	109·871	109·929	109·987	110·045
37	110·102	110·159	110·216	110·274	110·350	110·387	110·444	110·500	110·556	110·612
38	110·668	110·724	110·779	110·834	110·890	110·945	110·999	111·054	111·109	111·163
39	111·217	111·271	111·325	111·379	111·432	111·485	111·538	111·592	111·645	111·698
40	111·750									
	·00	·01	·02	·03	·04	·05	·06	·07	·08	·09

Table for converting the densities of the charges of powder

(*N.B.*—1 lb. of powder having a gravimetric density of 1·0 occupies a space of

Cubic Inches.	·0		·1		·2		·3		·4	
	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.
22	1·2583	·7947	1·2527	·7983	1·2470	·8019	1·2414	·8055	1·2359	·8091
23	1·2037	·8308	1·1985	·8344	1·1933	·8380	1·1882	·8416	1·1831	·8452
24	1·1535	·8669	1·1487	·8705	1·1440	·8741	1·1393	·8777	1·1346	·8814
25	1·1074	·9030	1·1029	·9067	1·0985	·9103	1·0942	·9139	1·0899	·9175
26	1·0648	·9391	1·0607	·9428	1·0566	·9464	1·0526	·9500	1·0486	·9536
27	1·0253	·9753	1·0215	·9789	1·0178	·9825	1·0141	·9861	1·0104	·9897
28	0·9887	1·0114	0·9852	1·0150	0·9817	1·0186	0·9782	1·0222	0·9748	1·0258
29	0·9546	1·0476	0·9513	1·0512	0·9481	1·0548	0·9448	1·0584	0·9416	1·0620
30	0·9228	1·0837	0·9197	1·0873	0·9167	1·0909	0·9137	1·0945	0·9107	1·0981
31	0·8930	1·1198	0·8902	1·1234	0·8873	1·1270	0·8845	1·1306	0·8817	1·1342
32	0·8651	1·1559	0·8624	1·1595	0·8598	1·1631	0·8571	1·1667	0·8544	1·1704
33	0·8389	1·1920	0·8364	1·1956	0·8339	1·1992	0·8314	1·2028	0·8289	1·2064
34	0·8142	1·2281	0·8118	1·2317	0·8095	1·2353	0·8071	1·2389	0·8048	1·2425
35	0·7910	1·2643	0·7887	1·2679	0·7865	1·2715	0·7842	1·2752	0·7820	1·2788
36	0·7690	1·3004	0·7669	1·3040	0·7648	1·3076	0·7626	1·3113	0·7605	1·3149
37	0·7482	1·3365	0·7462	1·3401	0·7442	1·3437	0·7422	1·3473	0·7402	1·3510
38	0·7285	1·3727	0·7266	1·3763	0·7247	1·3799	0·7228	1·3835	0·7209	1·3871
39	0·7098	1·4088	0·7080	1·4124	0·7062	1·4160	0·7044	1·4196	0·7026	1·4232
40	0·6921	1·4449	0·6904	1·4485	0·6887	1·4521	0·6869	1·4558	0·6852	1·4594
41	0·6752	1·4810	0·6736	1·4846	0·6719	1·4883	0·6703	1·4919	0·6687	1·4954
42	0·6591	1·5171	0·6576	1·5207	0·6560	1·5243	0·6545	1·5279	0·6529	1·5316
43	0·6438	1·5533	0·6423	1·5569	0·6408	1·5605	0·6393	1·5641	0·6379	1·5677
44	0·6292	1·5894	0·6277	1·5931	0·6263	1·5967	0·6249	1·6003	0·6235	1·6039
45	0·6152	1·6255	0·6138	1·6291	0·6125	1·6327	0·6111	1·6364	0·6098	1·6400
46	0·6018	1·6617	0·6005	1·6653	0·5992	1·6689	0·5979	1·6725	0·5966	1·6761
47	0·5890	1·6977	0·5878	1·7013	0·5865	1·7049	0·5853	1·7085	0·5840	1·7121
48	0·5768	1·7337	0·5756	1·7373	0·5744	1·7409	0·5732	1·7446	0·5720	1·7483
49	0·5650	1·7699	0·5638	1·7735	0·5627	1·7771	0·5615	1·7808	0·5604	1·7844
50	0·5537	1·8060	0·5526	1·8096	0·5515	1·8132	0·5504	1·8169	0·5493	1·8205
51	0·5428	1·8422	0·5418	1·8458	0·5407	1·8495	0·5396	1·8531	0·5386	1·8567
52	0·5324	1·8783	0·5314	1·8819	0·5303	1·8856	0·5293	1·8893	0·5283	1·8929
53	0·5223	1·9145	0·5214	1·9180	0·5204	1·9216	0·5194	1·9253	0·5184	1·9290
54	0·5127	1·9506	0·5117	1·9542	0·5108	1·9578	0·5098	1·9614	0·5089	1·9650
55	0·5033	1·9867	0·5024	1·9904	0·5015	1·9940	0·5006	1·9976	0·4997	2·0012
56	0·4944	2·0228	0·4935	2·0264	0·4926	2·0300	0·4917	2·0336	0·4909	2·0372
57	0·4857	2·0590	0·4848	2·0626	0·4839	2·0662	0·4831	2·0698	0·4823	2·0734
58	0·4773	2·0951	0·4765	2·0986	0·4757	2·1022	0·4749	2·1059	0·4740	2·1096
59	0·4692	2·1313	0·4684	2·1349	0·4676	2·1385	0·4668	2·1421	0·4661	2·1457
60	0·4614	2·1673	0·4606	2·1709	0·4599	2·1745	0·4591	2·1782	0·4583	2·1819

expressed in cubic inches per lb. into gravimetric densities.

27·684 cubic inches, which is equal to the density of water at 0° Centigrade.)

·5		·6		·7		·8		·9		Cubic Inches.
Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	
1·2304	·8127	1·2250	·8163	1·2196	·8199	1·2142	·8235	1·2089	·8272	22
1·1780	·8489	1·1730	·8525	1·1681	·8561	1·1632	·8597	1·1583	·8633	23
1·1300	·8850	1·1254	·8886	1·1209	·8922	1·1163	·8958	1·1118	·8994	24
1·0856	·9211	1·0814	·9247	1·0772	·9283	1·0730	·9319	1·0689	·9355	25
1·0447	·9572	1·0408	·9608	1·0369	·9644	1·0330	·9681	1·0291	·9717	26
1·0067	·9933	1·0031	·9969	0·9995	1·0005	0·9959	1·0041	0·9923	1·0078	27
0·9714	1·0294	0·9680	1·0331	0·9646	1·0367	0·9613	1·0403	0·9579	1·0440	28
0·9384	1·0656	0·9353	1·0692	0·9321	1·0728	0·9290	1·0764	0·9259	1·0800	29
0·9077	1·1017	0·9047	1·1053	0·9018	1·1089	0·8988	1·1126	0·8959	1·1162	30
0·8789	1·1378	0·8761	1·1414	0·8733	1·1450	0·8706	1·1486	0·8678	1·1523	31
0·8518	1·1740	0·8492	1·1776	0·8466	1·1812	0·8440	1·1848	0·8415	1·1884	32
0·8264	1·2101	0·8239	1·2737	0·8215	1·2173	0·8191	1·2209	0·8166	1·2245	33
0·8024	1·2462	0·8001	1·2498	0·7978	1·2534	0·7955	1·2571	0·7932	1·2607	34
0·7798	1·2824	0·7776	1·2860	0·7755	1·2896	0·7733	1·2932	0·7711	1·2968	35
0·7585	1·3185	0·7564	1·3221	0·7543	1·3257	0·7523	1·3293	0·7502	1·3329	36
0·7382	1·3546	0·7363	1·3582	0·7343	1·3618	0·7324	1·3654	0·7304	1·3691	37
0·7191	1·3907	0·7172	1·3943	0·7153	1·3979	0·7135	1·4015	0·7117	1·4051	38
0·7009	1·4268	0·6991	1·4304	0·6973	1·4341	0·6955	1·4377	0·6938	1·4413	39
0·6835	1·4630	0·6819	1·4666	0·6802	1·4702	0·6785	1·4738	0·6769	1·4774	40
0·6671	1·4990	0·6655	1·5026	0·6639	1·5063	0·6623	1·5099	0·6607	1·5135	41
0·6514	1·5352	0·6499	1·5388	0·6483	1·5425	0·6468	1·5461	0·6453	1·5497	42
0·6364	1·5713	0·6349	1·5750	0·6335	1·5786	0·6320	1·5822	0·6306	1·5858	43
0·6221	1·6075	0·6207	1·6111	0·6193	1·6147	0·6179	1·6183	0·6166	1·6219	44
0·6084	1·6436	0·6071	1·6472	0·6058	1·6508	0·6045	1·6544	0·6031	1·6581	45
0·5954	1·6797	0·5941	1·6833	0·5928	1·6869	0·5915	1·6905	0·5903	1·6941	46
0·5828	1·7157	0·5816	1·7193	0·5804	1·7229	0·5792	1·7265	0·5780	1·7301	47
0·5708	1·7519	0·5696	1·7555	0·5685	1·7591	0·5673	1·7627	0·5661	1·7663	48
0·5593	1·7880	0·5581	1·7917	0·5570	1·7953	0·5559	1·7989	0·5548	1·8025	49
0·5482	1·8242	0·5471	1·8278	0·5460	1·8314	0·5450	1·8350	0·5439	1·8386	50
0·5376	1·8603	0·5365	1·8639	0·5355	1·8675	0·5344	1·8712	0·5334	1·8748	51
0·5273	1·8965	0·5263	1·9001	0·5253	1·9037	0·5243	1·9073	0·5233	1·9109	52
0·5174	1·9326	0·5165	1·9362	0·5155	1·9398	0·5146	1·9434	0·5136	1·9470	53
0·5080	1·9686	0·5070	1·9723	0·5061	1·9759	0·5052	1·9794	0·5043	1·9830	54
0·4988	2·0048	0·4979	2·0084	0·4970	2·0121	0·4961	2·0157	0·4952	2·0193	55
0·4900	2·0408	0·4891	2·0445	0·4882	2·0481	0·4874	2·0517	0·4865	2·0554	56
0·4815	2·0770	0·4806	2·0806	0·4798	2·0842	0·4790	2·0878	0·4781	2·0915	57
0·4732	2·1133	0·4724	2·1169	0·4716	2·1204	0·4708	2·1240	0·4700	2·1277	58
0·4653	2·1493	0·4645	2·1529	0·4637	2·1565	0·4629	2·1601	0·4622	2·1637	59
0·4576	2·1855	0·4568	2·1891	0·4561	2·1927	0·4553	2·1963	0·4546	2·1999	60

Table for converting the densities of the charges of powder

Cubic Inches.	·0		·1		·2		·3		·4	
	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.
61	0·4538	2·2035	0·4531	2·2071	0·4523	2·2108	0·4516	2·2144	0·4509	2·2180
62	0·4465	2·2396	0·4458	2·2432	0·4451	2·2467	0·4444	2·2503	0·4437	2·2540
63	0·4394	2·2758	0·4387	2·2795	0·4380	2·2831	0·4373	2·2867	0·4366	2·2903
64	0·4326	2·3118	0·4319	2·3154	0·4312	2·3191	0·4305	2·3227	0·4299	2·3263
65	0·4259	2·3479	0·4253	2·3515	0·4246	2·3551	0·4240	2·3587	0·4233	2·3624
66	0·4194	2·3843	0·4188	2·3879	0·4182	2·3914	0·4176	2·3950	0·4169	2·3986
67	0·4132	2·4201	0·4126	2·4237	0·4120	2·4274	0·4114	2·4310	0·4107	2·4347
68	0·4071	2·4564	0·4065	2·4600	0·4059	2·4637	0·4053	2·4673	0·4047	2·4709
69	0·4012	2·4925	0·4006	2·4961	0·4000	2·4997	0·3995	2·5033	0·3989	2·5069
70	0·3954	2·5287	0·3949	2·5323	0·3943	2·5359	0·3938	2·5395	0·3932	2·5431
71	0·3899	2·5647	0·3894	2·5683	0·3888	2·5719	0·3883	2·5755	0·3877	2·5791
72	0·3845	2·6008	0·3839	2·6045	0·3834	2·6081	0·3829	2·6117	0·3824	2·6153
73	0·3792	2·6369	0·3787	2·6405	0·3782	2·6441	0·3777	2·6477	0·3772	2·6514
74	0·3741	2·6730	0·3736	2·6766	0·3731	2·6802	0·3726	2·6838	0·3721	2·6875
75	0·3691	2·7093	0·3686	2·7129	0·3681	2·7165	0·3676	2·7201	0·3672	2·7236
76	0·3643	2·7453	0·3638	2·7489	0·3633	2·7525	0·3628	2·7561	0·3624	2·7597
77	0·3595	2·7814	0·3591	2·7850	0·3586	2·7886	0·3581	2·7922	0·3577	2·7958
78	0·3549	2·8174	0·3545	2·8210	0·3540	2·8246	0·3536	2·8282	0·3531	2·8318
79	0·3504	2·8535	0·3500	2·8571	0·3495	2·8607	0·3491	2·8643	0·3487	2·8679
80	0·3461	2·8896	0·3456	2·8933	0·3452	2·8969	0·3448	2·9005	0·3443	2·9041
81	0·3418	2·9258	0·3414	2·9294	0·3409	2·9331	0·3405	2·9367	0·3401	2·9403
82	0·3376	2·9620	0·3372	2·9656	0·3368	2·9692	0·3364	2·9728	0·3360	2·9764
83	0·3335	2·9981	0·3331	3·0017	0·3327	3·0053	0·3323	3·0090	0·3319	3·0126
84	0·3296	3·0342	0·3292	3·0379	0·3288	3·0415	0·3284	3·0451	0·3280	3·0487
85	0·3257	3·0704	0·3253	3·0741	0·3249	3·0777	0·3245	3·0813	0·3242	3·0849
86	0·3219	3·1065	0·3215	3·1101	0·3212	3·1137	0·3208	3·1173	0·3204	3·1209
87	0·3182	3·1425	0·3178	3·1461	0·3175	3·1497	0·3171	3·1533	0·3168	3·1569
88	0·3146	3·1787	0·3142	3·1823	0·3139	3·1859	0·3135	3·1895	0·3132	3·1931
89	0·3110	3·2149	0·3107	3·2185	0·3103	3·2221	0·3100	3·2257	0·3096	3·2293
90	0·3076	3·2510	0·3072	3·2546	0·3069	3·2582	0·3066	3·2618	0·3062	3·2654
91	0·3042	3·2871	0·3039	3·2907	0·3035	3·2943	0·3032	3·2979	0·3029	3·3015
92	0·3009	3·3232	0·3006	3·3268	0·3003	3·3304	0·2999	3·3341	0·2996	3·3377
93	0·2977	3·3593	0·2974	3·3629	0·2970	3·3665	0·2967	3·3701	0·2964	3·3738
94	0·2945	3·3955	0·2942	3·3991	0·2939	3·4027	0·2936	3·4063	0·2933	3·4099
95	0·2914	3·4316	0·2911	3·4352	0·2908	3·4388	0·2905	3·4424	0·2902	3·4460
96	0·2884	3·4677	0·2881	3·4713	0·2878	3·4749	0·2875	3·4785	0·2872	3·4822
97	0·2854	3·5038	0·2851	3·5074	0·2848	3·5111	0·2845	3·5147	0·2842	3·5183
98	0·2825	3·5400	0·2822	3·5436	0·2819	3·5472	0·2816	3·5508	0·2813	3·5544
99	0·2796	3·5761	0·2794	3·5797	0·2791	3·5833	0·2788	3·5869	0·2785	3·5905

expressed in cubic inches per lb. into gravimetric densities—continued.

·5		·6		·7		·8		·9		Cubic Inches.
Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	
0·4501	2·2216	0·4494	2·2252	0·4487	2·2288	0·4480	2·2324	0·4472	2·2360	61
0·4429	2·2577	0·4422	2·2614	0·4415	2·2650	0·4408	2·2686	0·4401	2·2722	62
0·4360	2·2938	0·4353	2·2974	0·4346	2·3010	0·4339	2·3047	0·4332	2·3083	63
0·4292	2·3299	0·4285	2·3335	0·4279	2·3371	0·4272	2·3407	0·4266	2·3443	64
0·4227	2·3660	0·4220	2·3697	0·4214	2·3733	0·4207	2·3770	0·4201	2·3806	65
0·4163	2·4021	0·4157	2·4057	0·4151	2·4093	0·4144	2·4130	0·4138	2·4166	66
0·4101	2·4384	0·4095	2·4420	0·4089	2·4456	0·4083	2·4492	0·4077	2·4528	67
0·4041	2·4745	0·4035	2·4781	0·4030	2·4817	0·4024	2·4853	0·4018	2·4889	68
0·3983	2·5105	0·3977	2·5141	0·3972	2·5177	0·3966	2·5214	0·3960	2·5251	69
0·3927	2·5467	0·3921	2·5503	0·3916	2·5539	0·3910	2·5575	0·3905	2·5611	70
0·3872	2·5827	0·3866	2·5863	0·3861	2·5899	0·3856	2·5935	0·3850	2·5972	71
0·3818	2·6189	0·3813	2·6225	0·3808	2·6261	0·3803	2·6297	0·3797	2·6333	72
0·3767	2·6550	0·3761	2·6586	0·3756	2·6622	0·3751	2·6658	0·3746	2·6694	73
0·3716	2·6911	0·3711	2·6947	0·3706	2·6983	0·3701	2·7020	0·3696	2·7056	74
0·3667	2·7272	0·3662	2·7308	0·3657	2·7344	0·3652	2·7381	0·3647	2·7417	75
0·3619	2·7633	0·3614	2·7669	0·3609	2·7706	0·3605	2·7742	0·3600	2·7778	76
0·3572	2·7994	0·3568	2·8030	0·3563	2·8066	0·3558	2·8102	0·3554	2·8138	77
0·3527	2·8354	0·3522	2·8390	0·3518	2·8425	0·3513	2·8462	0·3509	2·8498	78
0·3482	2·8716	0·3478	2·8752	0·3474	2·8788	0·3469	2·8824	0·3465	2·8860	79
0·3439	2·9077	0·3435	2·9114	0·3430	2·9150	0·3426	2·9186	0·3422	2·9222	80
0·3397	2·9439	0·3393	2·9475	0·3388	2·9512	0·3384	2·9548	0·3380	2·9584	81
0·3356	2·9800	0·3352	2·9836	0·3348	2·9873	0·3343	2·9910	0·3339	2·9946	82
0·3315	3·0162	0·3311	3·0198	0·3308	3·0234	0·3304	3·0270	0·3300	3·0306	83
0·3276	3·0523	0·3272	3·0560	0·3268	3·0596	0·3265	3·0632	0·3261	3·0668	84
0·3238	3·0885	0·3234	3·0921	0·3230	3·0957	0·3227	3·0993	0·3223	3·1029	85
0·3200	3·1245	0·3197	3·1281	0·3193	3·1317	0·3189	3·1353	0·3186	3·1389	86
0·3164	3·1606	0·3160	3·1642	0·3157	3·1678	0·3153	3·1715	0·3149	3·1751	87
0·3128	3·1967	0·3125	3·2003	0·3121	3·2039	0·3118	3·2076	0·3114	3·2112	88
0·3093	3·2329	0·3090	3·2365	0·3086	3·2401	0·3083	3·2438	0·3079	3·2474	89
0·3059	3·2690	0·3056	3·2727	0·3052	3·2763	0·3049	3·2799	0·3045	3·2835	90
0·3025	3·3051	0·3022	3·3088	0·3019	3·3124	0·3016	3·3160	0·3012	3·3196	91
0·2993	3·3413	0·2990	3·3449	0·2986	3·3485	0·2983	3·3521	0·2980	3·3557	92
0·2961	3·3774	0·2958	3·3810	0·2955	3·3846	0·2951	3·3882	0·2948	3·3918	93
0·2930	3·4135	0·2926	3·4171	0·2923	3·4207	0·2920	3·4244	0·2917	3·4280	94
0·2899	3·4496	0·2896	3·4533	0·2893	3·4569	0·2890	3·4605	0·2887	3·4641	95
0·2869	3·4858	0·2866	3·4894	0·2863	3·4930	0·2860	3·4966	0·2857	3·5002	96
0·2839	3·5219	0·2836	3·5255	0·2833	3·5291	0·2831	3·5327	0·2828	3·5363	97
0·2810	3·5580	0·2807	3·5616	0·2804	3·5652	0·2802	3·5688	0·2799	3·5725	98
0·2782	3·5941	0·2780	3·5977	0·2777	3·6014	0·2774	3·6050	0·2771	3·6086	99

Table for converting the densities of the charges of powder

Cubic Inches.	·0		·1		·2		·3		·4	
	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.
100	0·2768	3·6122	0·2766	3·6158	0·2763	3·6194	0·2760	3·6230	0·2757	3·6266
101	0·2741	3·6483	0·2738	3·6519	0·2736	3·6555	0·2733	3·6592	0·2730	3·6628
102	0·2714	3·6844	0·2711	3·6881	0·2709	3·6917	0·2706	3·6953	0·2704	3·6989
103	0·2688	3·7206	0·2685	3·7242	0·2683	3·7278	0·2680	3·7314	0·2677	3·7350
104	0·2662	3·7567	0·2659	3·7603	0·2657	3·7639	0·2654	3·7675	0·2652	3·7711
105	0·2637	3·7928	0·2634	3·7964	0·2632	3·8000	0·2629	3·8036	0·2627	3·8073
106	0·2612	3·8289	0·2609	3·8325	0·2607	3·8361	0·2604	3·8397	0·2602	3·8434
107	0·2587	3·8650	0·2585	3·8687	0·2582	3·8723	0·2580	3·8759	0·2578	3·8795
108	0·2563	3·9012	0·2561	3·9048	0·2559	3·9084	0·2556	3·9120	0·2554	3·9156
109	0·2540	3·9373	0·2537	3·9409	0·2535	3·9445	0·2533	3·9481	0·2531	3·9517
110	0·2517	3·9734	0·2514	3·9770	0·2512	3·9806	0·2510	3·9843	0·2508	3·9879
111	0·2494	4·0095	0·2492	4·0131	0·2490	4·0168	0·2487	4·0204	0·2485	4·0240
112	0·2472	4·0457	0·2470	4·0493	0·2467	4·0529	0·2465	4·0565	0·2463	4·0601
113	0·2450	4·0818	0·2448	4·0854	0·2446	4·0890	0·2443	4·0926	0·2441	4·0962
114	0·2428	4·1179	0·2426	4·1215	0·2424	4·1251	0·2422	4·1287	0·2420	4·1324
115	0·2407	4·1540	0·2405	4·1576	0·2403	4·1612	0·2401	4·1649	0·2399	4·1685
116	0·2387	4·1901	0·2385	4·1938	0·2382	4·1974	0·2380	4·2010	0·2378	4·2046
117	0·2366	4·2263	0·2364	4·2299	0·2362	4·2335	0·2360	4·2371	0·2358	4·2407
118	0·2346	4·2624	0·2344	4·2660	0·2342	4·2696	0·2340	4·2732	0·2338	4·2768
119	0·2326	4·2985	0·2324	4·3021	0·2322	4·3057	0·2320	4·3093	0·2319	4·3129
120	0·2307	4·3346	0·2305	4·3382	0·2303	4·3419	0·2301	4·3455	0·2299	4·3491

expressed in cubic inches per lb. into gravimetric densities—continued.

·5		·6		·7		·8		·9		Cubic Inches.
Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	Density.	Volumes.	
0·2755	3·6302	0·2752	3·6339	0·2749	3·6375	0·2746	3·6411	0·2744	3·6447	100
0·2727	3·6664	0·2725	3·6700	0·2722	3·6736	0·2719	3·6772	0·2717	3·6808	101
0·2701	3·7025	0·2698	3·7061	0·2696	3·7097	0·2693	3·7133	0·2690	3·7170	102
0·2675	3·7386	0·2672	3·7422	0·2669	3·7458	0·2667	3·7495	0·2664	3·7531	103
0·2649	3·7747	0·2647	3·7783	0·2644	3·7820	0·2642	3·7856	0·2639	3·7892	104
0·2624	3·8109	0·2622	3·8145	0·2619	3·8181	0·2617	3·8217	0·2614	3·8253	105
0·2599	3·8470	0·2597	3·8506	0·2594	3·8542	0·2592	3·8578	0·2590	3·8614	106
0·2575	3·8831	0·2573	3·8867	0·2570	3·8903	0·2568	3·8939	0·2566	3·8976	107
0·2552	3·9192	0·2549	3·9228	0·2546	3·9265	0·2544	3·9301	0·2542	3·9337	108
0·2528	3·9554	0·2525	3·9590	0·2523	3·9626	0·2521	3·9662	0·2519	3·9698	109
0·2505	3·9915	0·2503	3·9951	0·2501	3·9987	0·2499	4·0023	0·2496	4·0059	110
0·2483	4·0276	0·2481	4·0312	0·2478	4·0348	0·2476	4·0384	0·2474	4·0420	111
0·2461	4·0637	0·2459	4·0673	0·2456	4·0709	0·2454	4·0746	0·2452	4·0782	112
0·2439	4·0998	0·2437	4·1035	0·2435	4·1071	0·2433	4·1107	0·2431	4·1143	113
0·2418	4·1360	0·2416	4·1396	0·2414	4·1432	0·2412	4·1468	0·2409	4·1504	114
0·2397	4·1721	0·2395	4·1757	0·2393	4·1793	0·2391	4·1829	0·2389	4·1865	115
0·2376	4·2082	0·2374	4·2118	0·2372	4·2154	0·2370	4·2190	0·2368	4·2227	116
0·2356	4·2443	0·2354	4·2479	0·2352	4·2516	0·2350	4·2552	0·2348	4·2588	117
0·2336	4·2805	0·2334	4·2841	0·2332	4·2877	0·2330	4·2913	0·2328	4·2949	118
0·2317	4·3166	0·2315	4·3202	0·2313	4·3238	0·2311	4·3274	0·2309	4·3310	119
0·2297	4·3527	0·2295	4·3563	0·2294	4·3599	0·2292	4·3635	0·2290	4·3671	120

XI.

PRELIMINARY NOTE ON THE PRESSURE DEVELOPED BY SOME NEW EXPLOSIVES

(*Proceedings of the Royal Society*, 1892.)

For a considerable time I have, with the assistance of Sir F. Abel and Professor Dewar, been engaged in researches upon the new explosives which during the last few years have attracted so much attention, and which apparently are destined to do much in developing the power of modern artillery.

From the nature of these researches and the considerable scale upon which they have to be conducted, as well as from certain difficulties which have manifested themselves, I am not at present in a position to submit to the Royal Society the results of these experiments; but, as one particular portion throws light upon a question of considerable importance, I propose very shortly to give the results at which I have arrived, leaving fuller details for a subsequent communication.

Artillerists of all nations are pretty well agreed that, save under exceptional circumstances, the maximum working pressure in a gun should not exceed 17 tons per square inch or, say, 2500 atmospheres. The reasons for this limitation are weighty, but I need not here discuss them. Now, taking cordite and pebble-powder as illustrations, since we can, even in guns not designed to fire the former explosive, obtain with the same maximum pressure, energies higher than those obtained with pebble-powder by nearly 50 per cent., it is obvious that this extra energy must be obtained from the development of higher pressures in the forward portions of the guns, and it naturally became a question of considerable importance to determine over what surface these higher pressures extended, and to ascertain if they in any serious degree affected the safety of the chase.

At Woolwich, to settle this point, certain guns were prepared in which crusher-gauges were placed at various points along the bore, and results were obtained to which I shall presently more

particularly allude; but, considerable doubt having been thrown on the reliability of these crusher-gauges, I considered it desirable in a matter of so great importance to ascertain the pressures by altogether independent means, and thus either confirm the crusher-gauge results, or, if the two sets of results should prove to be not altogether in accordance, to throw some light upon the causes of such discrepancies as might exist.

The crusher-gauge is, to those who interest themselves with such subjects, so well known, that I shall not attempt here to describe it, and I will only say that I have very great confidence in the accuracy of its results when properly used. Personally I have during the last twenty-five years made many thousand observations with these gauges, and when properly prepared and judiciously used, not only have I found their results accordant *inter se*, but I have by totally different determinations corroborated their accuracy. But I have always held that this gauge and all similar gauges will cease to be either reliable or accurate if there be any probability of the products of explosion being projected into the gauge at a high velocity, the energy stored up in such products being impressed on the gauge in the form of pressure, and this contingency might and does arise either when the gauge is placed in the forward part of a gun, where necessarily the products are in rapid motion, or in the case of the detonation of a high explosive; but, as I have gone pretty fully into this question elsewhere, I need not here pursue the subject further.

The crusher-gauge determinations for cordite, made at Woolwich for the Explosives Committee, under the presidency of Sir F. Abel, having been made in a 4·7-inch quick-firing gun, I arranged a similar gun in such a manner that I was able to obtain a curve determined from the time at which the projectile passed sixteen points arranged along the bore. From this curve, by methods I have elsewhere described, the curve giving the velocity at all points of the bore can be deduced, and from the curve of velocity the pressures generating these velocities can also be deduced.

For the particular purpose of this investigation it was desirable to compare the pressures of different explosives, and the present note gives the result of four explosives differing widely in nature and in composition.

The explosives used were as follows:—

a. Ordinary pebble-powder of the service. A charge of 12 lbs. was used; this charge gave rise to a mean pressure of 15·9 tons per

square inch (maximum, 16·8; minimum, 14·9), or a mean of 2424 atmospheres (maximum, 2566; minimum, 2277) as determined by the crusher-gauge in the powder chamber. It gave to a 45-lb. projectile a mean muzzle velocity of 1839 feet per second, thus developing a muzzle energy of 1055 foot-tons. A gramme of pebble-powder at a temperature of 0° Cent. and a barometric pressure of 760 mm. generates 280 c.c. of permanent gas, and develops 720 grm.-units of heat.

b. Amide powder, consisting of 40 per cent. of potassic nitrate, 38 per cent. of ammonia nitrate, and 22 per cent. of charcoal. The charge in this case was 10 lbs. 8 oz., and the mean crusher-gauge pressure was 15·3 tons per square inch (maximum, 16·4; minimum, 14·2), or a mean of 2332 atmospheres (maximum, 2500; minimum, 2165); the muzzle velocity with the same projectile was 2036 feet per second, and the muzzle energy 1293 foot-tons. A gramme of amide powder generates 400 c.c. of permanent gases, and develops 821 units of heat.

c. Ballistite. With this true smokeless powder the charge was reduced to 5 lbs. 8 oz., the sides of the cubes being 0·2 inch. The mean crusher-gauge pressure was 14·3 tons per square inch (maximum, 14·5; minimum, 14·1), or a mean of 2180 atmospheres (maximum, 2210; minimum, 2142). The muzzle velocity was 2140 feet per second, and the muzzle energy 1429 foot-tons. A gramme of ballistite generates 615 c.c. of permanent gases, and gives rise to 1365 grm.-units of heat.

d. With the fourth explosive, cordite, a charge of 5 lbs. 10 oz. of 0·2 inch diameter was fired. The mean chamber crusher-gauge pressure was 13·3 tons per square inch (maximum, 13·6; minimum, 12·9), or a mean of 2027 atmospheres (maximum, 2070; minimum, 1970). The muzzle velocity was 2146 feet per second, and the muzzle energy 1437 foot-tons. A gramme of cordite generates 700 c.c. of permanent gases at 0° Cent. and 760 mm. of barometric pressure. The quantity of heat developed is 1260 grm.-units. In the case of this explosive, as well as in that of ballistite, a considerable quantity of aqueous vapour has to be added to the permanent gases.

The results of these observations are graphically given in the figure (coloured diagram, p. 466). The ordinates show both the positions at which the pressures were determined and the magnitudes of these pressures. On the axis of abscissæ is shown the travel of the shot in feet.

Each curve is deduced from the mean of three * complete rounds, that is to say, three rounds with the breech and three with the muzzle plugs, or six in all.

In the calculation of the pressures, it is assumed that before and after the complete ignition of the explosive the pressures will uniformly increase and then uniformly decrease, following the laws regulating the relation between the pressure and volume when permanent gases are permitted to expand with production of work.

It is in the highest degree improbable that in any experiment is this assumption strictly true. In the case of "brisante" powders, and of high explosives which can be detonated, we know that even in moderately-sized chambers there are wide variations in pressure; and even when there is comparatively slow combustion, as with ballistite and cordite, it appears probable that the generation of a considerable quantity of the gases may take place in different portions of the bore, giving rise to a corresponding difference in the pressure, and it may be that a portion of the discrepancies of the crusher-gauge when placed in forward positions in the bore, to which I shall presently allude, are due to this cause.

But such irregularities would not very seriously alter the curves shown in the figure. The areas included between the final ordinate, the curve, and the axis of abscissæ, being the total energy impressed on the projectile, would of course remain unaltered; but the curves, instead of the regular figure there shown, would have a wavy outline, and would show several maxima and minima. These irregularities of pressure are of no appreciable importance when the strength of the gun, in a radial direction, is considered.

From the same plate can be at once obtained the pressures for the four explosives at any point of the bore; but for the purpose of applying these results to other guns, I give in the annexed table (p. 466) for different densities of the products of explosion (1) the pressure which has been determined in a closed vessel, (2) the pressure at the same density which has been found to exist in the bore of the 4·7-inch gun where the gases have been expanded, doing work on the projectile.

It must be understood that the differences existing between the close-vessel pressures and the pressures observed in the bore at the higher gravimetric densities are, in great measure, due to the explosive

* Since these experiments were carried out, a second set of induction coils has been added, so that a single round gives simultaneously the times both at the breech and the muzzle plugs.

at these densities not being fully consumed. An examination of the results obtained would lead to the conclusion that with the particular size of cordite employed tolerably complete combustion cannot be assumed to have taken place until the projectile has travelled some 6 or 7 feet through the bore. Indeed, if the size of cordite fired in

Comparison of pressures in closed vessel with those in 4·7-inch quick-firing gun.

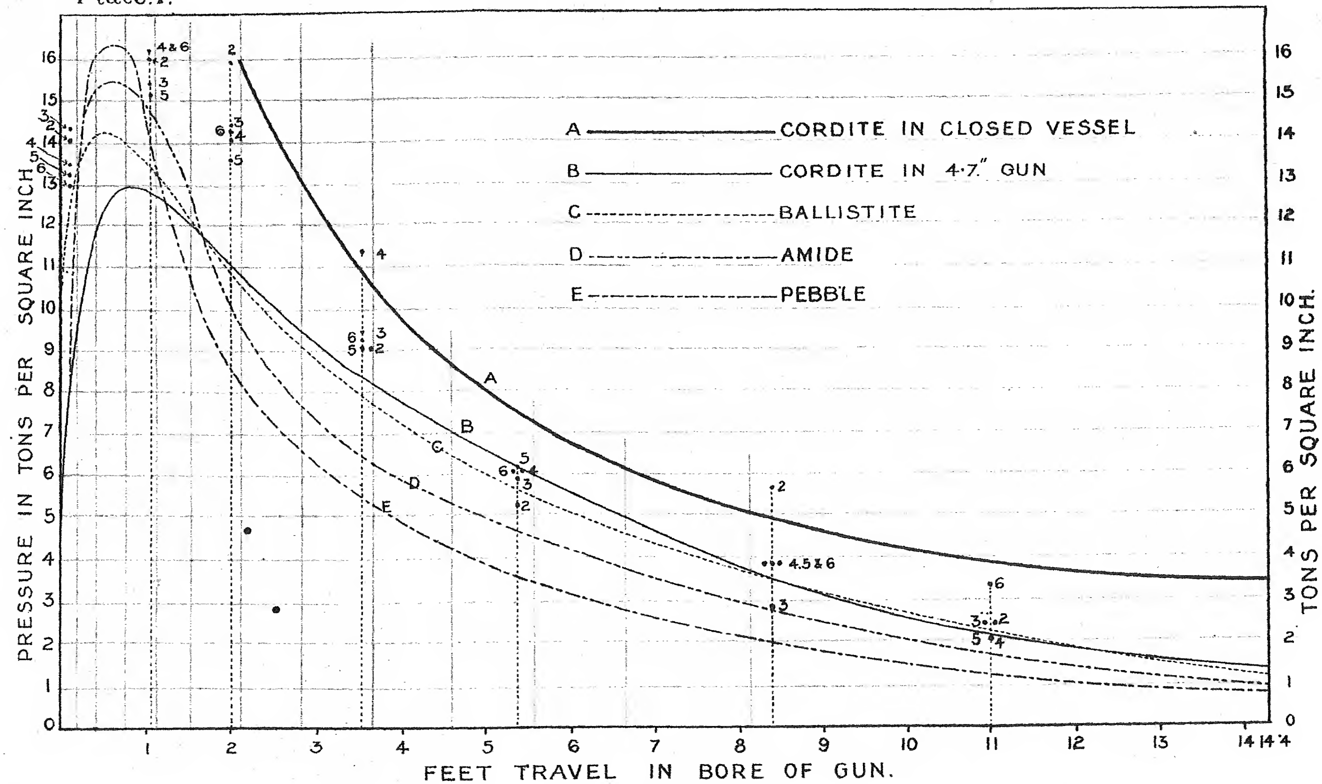
Peeble Powder.			Amide Powder.		
Density.	Pressure.		Density.	Pressure.	
	In closed vessel.*	In gun.		In closed vessel.	In gun.
0·65	17·68	15·82			
0·60	15·55	14·55			
0·55	13·62	11·84	0·55	25·50	15·50
0·50	11·85	9·31	0·50	22·00	13·75
0·45	10·23	8·12	0·45	19·10	12·10
0·40	8·73	7·00	0·40	16·50	10·00
0·35	7·35	6·11	0·35	14·00	8·34
0·30	6·07	5·21	0·30	11·90	7·05
0·25	4·88	4·20	0·25	9·80	5·88
0·20	3·77	2·95	0·20	7·75	4·55
0·15	2·73	1·82	0·15	5·00	3·10
0·10	1·76	0·70	0·10	3·55	1·32
Ballistite.			Cordite.		
0·26	20·80	13·45	0·26	21·75	12·50
0·24	19·00	12·70	0·24	19·80	11·95
0·22	17·10	11·83	0·22	17·90	11·28
0·20	15·30	10·77	0·20	16·00	10·60
0·18	13·40	9·75	0·18	14·20	9·85
0·16	11·70	8·70	0·16	12·30	9·10
0·14	10·00	7·50	0·14	10·50	8·16
0·12	8·40	6·52	0·12	8·70	7·08
0·10	6·60	5·29	0·10	7·10	5·70
0·08	5·00	4·08	0·08	5·40	4·01
0·06	3·50	2·54	0·06	3·80	2·33
0·05	2·80	1·64	0·05	3·00	1·57

* *Phil. Trans.*, part i., 1875, p. 129.

this gun be even slightly increased, a portion of the cordite is blown from the muzzle unburned, and it is one of the most striking proofs of the regular combustion of the explosive that in all such recovered cordite the diameter is so uniformly decreased that it might readily be mistaken for newly-manufactured cordite of smaller dimensions.

I now make a comparison between the pressures given by cordite, as shown on curve B (see coloured diagram on opposite page), and

Plate. I.



PRESSURE IN TONS PER SQUARE INCH
TONS PER SQUARE INCH.
FEET TRAVEL IN BORE OF GUN.
A —— CORDITE IN CLOSED VESSEL
B —— CORDITE IN 4·7." GUN
C ------ BALLISTITE
D —·— AMIDE
E — — PEBBLE

those obtained from crusher-gauges. To facilitate this comparison I have added to the pressure curves I have described a curve showing the pressures developed by cordite when fired in a close vessel, and I have further added the results of five rounds of cordite fired for the Explosives Committee in the crusher-gauge gun, the pressure of each individual round at each point of observation being indicated.

The sample of cordite used in these experiments was not of the same make as that employed in my own. The pressures given on the axis of y denote those taken in the powder chamber, and are comparable with the crusher-gauge pressures I have given as derived from my own experiments. It will be observed that the mean chamber pressure indicated is two- or three-tenths of a ton higher than that I obtained; but it will be further observed that if I attempt to draw a pressure curve through the mean of the crusher-gauge observation, such curve would indicate pressures far higher than are necessary and sufficient to develop the work impressed on the projectile.

Again, the pressures indicated after the projectile has moved 1 foot are about 2 tons per square inch higher than those observed in the powder chamber, and it will be further noticed that not only are these observations, at all events at certain points, considerably too high, but they exhibit in the forward part of the bore variations quite unknown when the pressures are taken in the powder chamber.

Thus, in the particular experiments I am discussing, the mean pressure in the powder chamber being about 13·5 tons, the extreme variation in the five rounds amounts only to about 1⅓ tons per square inch, while the crusher-gauge placed in the chase at a point about 8½ feet from the seat of the shot, gave in the same number of rounds an extreme variation of 3 tons per square inch, the mean pressures being only about 4 tons; and it will further be noted that, while some of the rounds indicated pressures below those deduced by the method I have described, other rounds at the same point indicated pressures even exceeding those which would have existed under the same gravimetric densities in a close vessel. It may also be noted that from the crusher-gauge experiments, round 5 should have given the lowest muzzle energy of the series; as a matter of fact it gave the highest.

My conclusion, therefore, is that, although crusher-gauges placed in the chase may, and doubtless do, give valuable comparative results, they cannot be relied on for absolute determinations, unless confirmed by observations altogether independent in their nature.

XII.

RESEARCHES ON EXPLOSIVES. PRELIMINARY NOTE.

(*Proceedings of the Royal Society*, 1894.)

THE researches on which I, in conjunction with Sir F. Abel, have been engaged for very many years, have had their scope so altered and extended by the rapid advances which have been made in the science of explosives, that we have been unable to lay before the Society the results of the many hundreds of experiments under varied conditions which I have carried out. We are desirous also of clearing up some difficulties which have presented themselves with certain modern explosives when dealing with high densities and pressures; but the necessary investigations have occupied so much time, that I am induced to lay a few of our results before the Society, trusting, however, that before long we may be able to submit a more complete memoir.

A portion of our researches includes investigations into the transformation and ballistic properties of powders varying greatly in composition, but of which potassium nitrate is the chief constituent. In this preliminary note I propose to refer to powders of this description chiefly for purposes of comparison, and shall devote my attention principally to guncotton and to those modern explosives of which guncotton forms a principal ingredient.

In determining the transformation experienced during explosion, the same arrangements for firing the explosive and collecting the gases were followed as are described in our earlier researches,* and the gases themselves were, after being sealed, analysed either under the personal superintendence of Sir F. Abel, or of Professor Dewar, and to Professor Dewar's advice and assistance I am indebted, I can hardly say to what extent.

The heat developed by explosion, and the quantity of permanent gases generated were also determined as described in our researches, but the amount of water formed plays so important a part in the

* *Phil. Trans.*, vol. clxv., p. 61.

transformation that special means were adopted in order to obtain this product with exactness.

The arrangement employed was as follows:—

After explosion the gases formed were allowed to escape through two U-tubes filled with pumice-stone and concentrated sulphuric acid; when the gases had all escaped the explosion cylinder was opened, and the water deposited at the bottom of the cylinder was collected in a sponge, placed in a closed glass vessel, and weighed. The cylinder was then nearly closed and heated, and a measured quantity of air was, by means of an aspirator, drawn slowly through the U-tubes till the cylinder was perfectly dry. This was easily ascertained by observing when moisture was no longer deposited on a cooled glass tube through which the air passed.

The -U tubes were then carefully weighed, the amount of moisture absorbed determined, and added to the quantity of water directly collected. The aqueous vapour in the air employed for drying was, for each experiment, determined and deducted from the gross amount.

Numerous experiments were made to ascertain the relation of the tension of the various explosives employed, to the gravimetric density of the charge when fired in a close vessel; but I do not propose here to pursue this part of our inquiry, both because the subject is too large to be treated of in a preliminary note, and because approximate values have already been published * for several of the explosives with which we have experimented.

With certain explosives, the possibility or probability of detonation was very carefully investigated. In some cases the explosive was merely placed in the explosion-vessel in close proximity to a charge of mercuric fulminate by which it was fired, but I found that the most satisfactory method of experiment was to place the charge to be experimented with in a small shell packed as tightly as possible, the shell then being placed in a large explosion-vessel and fired by means of mercuric fulminate. The tension in the small shell at the moment of fracture and the tension in the large explosion-vessel were in each experiment carefully measured.

It may be desirable here to explain that I do not consider the presence of a high pressure with any explosive as necessarily denoting detonation. With both cordite and guncotton I have developed enormous pressures, close upon 100 tons per square inch (about 15,000 atmospheres), but the former explosive I have not succeeded

* Noble, *Internal Ballistics*, 1892, p. 33; *Roy. Soc. Proc.* vol. lii., p. 128.

in detonating, while guncotton can be detonated with the utmost ease. It is obvious that if we suppose a small charge fired in a vessel impervious to heat, the rapidity or slowness of combustion will make no difference in the developed pressure, and that pressure will be the highest of which the explosive is capable, regard being of course had to the density of the charge. I say a small charge, because, if a large charge were in question, and explosion took place with extreme rapidity, the nascent gases may give rise to such whirlwinds of pressure, if I may use the term, that any means we may have of registering the tension will show pressures very much higher than would be registered were the gases, at the same temperature, in a state of quiescence. I have had innumerable proofs of this action, but it is evident that in a very small charge the nascent gases will have much less energy than in the case of a large charge occupying a considerable space.

The great increase in the magnitude of the charges fired from modern guns has rendered the question of erosion one of great importance. Few, who have not had actual experience, have any idea how rapidly with very large charges the surface of the bore is removed. Great attention has therefore been paid to this point, both in regard to the erosive power of different explosives and in regard to the capacity of different materials (chiefly different natures of steel) to resist the erosive action.

The method I adopted for this purpose consisted in allowing large charges to escape through a small vent. The amount of the metal removed by the passage of the products of explosion, which amount was determined by calibration, was taken as a measure of the erosive power of the explosive.

Experiments have also been made to determine the rate at which the products of explosion part with their heat to the surrounding envelope, the products of explosion being altogether confined. I shall only briefly allude to these experiments, as, although highly interesting, they have not been carried far enough to entitle me to speak with confidence as to final conclusions.

Turning now to ballistic results. The energies which the new explosives are capable of developing, and the high pressures at which the resulting gases are discharged from the muzzle of the gun, render length of bore of increased importance. With the object of ascertaining with more precision the advantages to be gained by length, the firm to which I belong has experimented with a 6-inch gun of 100 calibres in length. In the particular experi-

ments to which I refer, the velocity and energy generated has not only been measured at the muzzle, but the velocity and the pressure producing this velocity have been obtained for every point of the bore, consequently the loss of velocity and energy due to any particular shortening of the bore can be at once deduced.

These results have been obtained by measuring the velocities every round at sixteen points in the bore and at the muzzle. These data enable a velocity curve to be laid down, while from this curve the corresponding pressure curve can be calculated. The maximum chamber pressure obtained by these means is corroborated by simultaneous observations taken with crusher-gauges, and the internal ballistics of various explosives have thus been completely determined.

Commencing with guncotton, with which a very large number of analyses were made, with the view of determining whether there was any material difference in the decomposition dependent upon the pressure under which it was exploded, two descriptions were employed: one in the form of hank or strand, and the other in the form of compressed pellets. Both natures were approximately of the same composition, of Waltham-Abbey manufacture, containing in a dried sample about 4·4 per cent. of soluble cotton and 95·6 per cent. of insoluble. As used, it contained about 2·25 per cent. of moisture.

The following were the results of the analyses of the permanent gases. They are placed in five series, viz.:—

First.—Analyses showing the decomposition of the strand or hank guncotton. Second.—Analyses showing the decomposition of pellet guncotton.

In both these series the analyses are arranged in the order of the ascending pressures under which the decomposition took place.

Third and fourth.—Examples of the decomposition of strand and pellet guncotton when exploded by means of mercuric fulminate. And, fifth, a series showing the decomposition experienced by pellet guncotton saturated with from 25 to 30 per cent. of water, and detonated by means of a primer of dry guncotton and mercuric fulminate.

I leave these results for discussion in the memoir which Sir F. Abel and I hope before long to submit, and will only remark that, in Tables 1 and 2, the same peculiarity we have before remarked upon in reference to gunpowder, is again exhibited; I mean the marked manner in which the carbonic anhydride increases with the pressure. It will be noted that in Table 1 the volumes of carbonic anhydride and carbonic oxide are nearly exactly reversed;

TABLE 1.—*Results in volumes of the analyses of the permanent gases generated by the explosion of strand guncotton, arranged according to ascending pressures.*

Under pressure of gas.	Tons per square inch.										
	1·5	2·5	8·0	8·0	12·0	12·3	18·0	20·0	45·0 ?	48·0 ?	50·0 ?
CO_2 . . (vols.)	26·49	29·62	30·95	31·00	32·23	32·70	33·63	33·01	34·70	34·77	36·18
CO . . ,,	36·66	35·03	32·27	32·76	30·65	31·36	31·20	30·32	28·60	28·66	27·57
H . . ,,	19·68	17·13	19·10	18·80	20·38	19·23	17·99	18·25	16·56	17·48	16·76
N . . ,,	16·85	18·18	17·20	16·90	16·43	16·25	16·23	16·60	16·83	16·05	16·15
CH_4 . . ,,	0·32	0·04	0·48	0·54	0·31	0·46	0·95	1·82	3·31	3·04	3·34

TABLE 2.—*Similar analyses for pellet guncotton.*

Under pressure of gas.	Tons per square inch.									
	1·0	1·5	6·5	11·0	14·0	15·0	17·0	17·0	25·0	30·0
CO_2 . . . . . (vols.)	21·50	25·03	25·61	26·68	27·41	25·75	28·54	28·39	28·24	28·88
CO . . . . . ,,	39·70	36·85	39·51	36·97	37·23	38·00	35·52	36·41	34·94	35·64
H . . . . . ,,	22·83	21·00	18·80	19·59	19·37	19·71	18·47	19·64	20·30	20·50
N . . . . . ,,	15·58	15·88	15·97	15·91	15·35	15·26	16·08	14·90	15·59	14·98
CH_4 . . . . . ,,	0·39	1·24	0·11	0·85	0·64	1·28	1·39	0·66	0·93	

TABLE 3.—*Results of the analyses of strand guncotton when fired in a close vessel by detonation.*

	Pressure * per sq. inch. 1 ton.	3 tons.
CO_2 (vols.)	19·21	29·08
CO ,,	41·25	32·88
H ,,	23·07	20·14
N ,,	16·21	17·50
CH_4 ,,	0·26	0·75

* The pressures given are those due to the gravimetric density of the charge.

TABLE 4.—*Similar results for pellet guncotton.*

	Pressure per sq. inch. 3 tons.	10 tons.
CO_2 (vols.)	25·76	26·50
CO ,,	39·34	37·48
H ,,	18·71	20·97
N ,,	16·19	15·05
CH_4 ,,	Nil	Nil

TABLE 5.—*Results of analyses of saturated pellet guncotton fired in a close vessel by detonation.*

	Pressure per square inch.			
	Under 10 tons.	10·5 tons.	16 tons.	16·5 tons.
CO_2 (vols.)	32·14	33·25	32·93	35·60
CO ,,	27·04	25·90	27·25	23·43
H ,,	26·80	26·53	25·76	24·22
N ,,	13·83	14·32	14·06	15·25
CH_4 ,,	0·19	Nil	Nil	1·50

again, considering that the composition of the pellet and strand guncotton is practically the same, the distinct difference between the proportions of these products in the two series is sufficiently remarkable. It not improbably is connected with the rapidity of combustion of the two samples. Another striking peculiarity is the manner in which the CO_2 is increased (as exhibited in Table 5) when saturated pellet cotton is detonated.

Such are the average analyses of the permanent gases generated by the decomposition of guncotton under the various conditions I have described, and it will be evident from these analyses that the volumes of the permanent gases may be expected to differ to some very appreciable extent, depending both upon the density under which it is exploded, and also upon the mode of explosion. I have found it most convenient to explode the charges, the permanent gases from which were to be measured, under a pressure of about 10 tons per square inch (1524 atmospheres), and, under these circumstances, the average of several very accordant determinations

gave, at 0° Cent. and 760 mm. of mercury, 689 c.c. per gramme of strand guncotton and 725 c.c. per gramme of pellet guncotton.

At the temperature of explosion the whole of the water formed is in the gaseous state. It is therefore necessary, in order to obtain the total gaseous volume, to add to the above volumes of permanent gases the equivalent volume of aqueous vapour at the temperature and pressure stated. Now the quantity of water formed by the explosion of 129·6 grms. of guncotton was found to be 16·985 grms.; hence 1 grm. of guncotton generated 0·1311 grm. of water, equivalent to 162·6 c.c. of aqueous vapour, and the total volume of gaseous matter at the temperature and pressure stated is for strand guncotton 852·2 c.c. per gramme, for pellet 887·6 c.c.

The heat measured reached, with strand guncotton, 1068 grm.-units (water fluid), or 988 grm.-units (water gaseous), while with pellet guncotton these figures were 1037 or 957 grm.-units respectively.

Pellet guncotton made at Stowmarket generated 738 c.c. of permanent gas and 994 units of heat per gramme, while dinitro-cellulose containing 12·8 per cent. of nitrogen generated 748 c.c. of gas and 977 units of heat, the water in both cases being fluid.

Guncotton, both pellet and strand, I have detonated by means of mercuric fulminate with ease and certainty. The effect of employing this means of ignition in a close vessel is very striking, and the indications of intense heat are much more apparent than when the charge is fired in the ordinary way. This effect is probably partly due to an actual higher temperature, caused by the greater rapidity of combustion. I allude elsewhere to the extreme rapidity with which the gases part with their heat, but this higher heat is, I think, clearly indicated by the surfaces of the internal crusher-gauges becoming covered with innumerable small cracks, and by thin laminæ occasionally flaking off exposed surfaces; but perhaps the most striking proof of the violence of this detonation is shown by its action on a cast-iron shell fired as I have described; where no detonation takes place the shell is broken into fragments of various sizes, such as are familiar to all acquainted with the bursting of shell; but when detonation, with guncotton, for example, takes place, the whole shell is reduced to very minute fragments, and, what is more remarkable, two-thirds of the total weight are generally in the form of small peas and of the finest dust.

The ease with which guncotton can be detonated renders it unsuitable for use as a propulsive agent, unless this property be in some way neutralised. I have, therefore, made but few experiments

in this direction, and shall not further allude to them in this note, as more suitable explosives—explosives also of which guncotton is a principal component—have been elaborated; and these not only possess to the full the high ballistic properties of guncotton, but are more or less free from the tendency to detonate, which, however useful it may be in other directions, is a fatal objection to the employment of guncotton for propelling purposes.

Turning now to cordite; cordite consists, as is well known, of nitro-glycerine and guncotton as its main ingredients. As now made, it contains 37 per cent. of guncotton (trinitro-cellulose with a small proportion of soluble guncotton), 58 per cent. of nitro-glycerine, and 5 per cent. of a hydrocarbon known as vaselin. On account of the importance of this explosive, I have made numerous experiments, both with large and small charges, to determine the relation of the tension to the density of the charge. Up to densities of 0·55 the relation may be considered to be very approximately determined: above that density, although many determinations have been made, these determinations have shown such wide variations that they cannot, until certain discrepancies are explained, be assumed as at all accurate.

The average results of some of the analyses of the permanent gases are given below:—

The first four analyses were made from experiments with the earlier samples of cordite when tannin formed an ingredient of cordite. They are not, therefore, strictly comparable with the later analyses. There appears also to be a difference in the transformation, slight but decided, which the same cordite experiences, dependent upon the diameter of the cord; and this difference is shown at once in the analyses, in the volume of permanent gases, in the heat developed, and, I think, in the amount of aqueous vapour formed.

The following are some of the analyses:—

TABLE 6.

Pressure per square inch.

	0·048 Cordite.				0·225 Cordite.			
	2·5 tons.	6 tons.	10 tons.	14 tons.	10 tons.	12 tons.	11 tons.	14 tons.
CO_2 .	29·9	30·4	32·0	31·6	27·0	28·4	23·9	26·3
CO .	28·3	30·7	32·9	32·1	34·2	33·8	37·2	35·8
H .	19·3	20·0	18·0	21·6	26·9	24·4	28·4	26·1
N .	22·5	18·9	17·1	14·8	12·0	13·4	10·4	11·8
CH_4 .	traces.							

In the whole of these analyses the water formed by the explosion smelt strongly of ammonia.

The quantity of permanent gases measured, under the same conditions as in the case of guncotton, was found to be:—

For the earlier cordite, 655 vols.

For the present service cordite, 0·255 inch in diameter, 692 vols., and for that 0·048 inch in diameter, 698 vols. In the two latter samples the aqueous vapour was determined, and was found to amount to 20·257 grms. for the 0·255-inch cordite, and to 20·126 grms. for the 0·048-inch cordite; or, stating the result per gramme, these figures are respectively equivalent to 0·1563 grm., or 194 c.c. aqueous vapour, and to 0·1553 grm., or 192·5 c.c. per grm. of cordite.

Hence the total gaseous products generated by the explosion of cordite amount per grm. to 886 c.c. for the 0·255-inch cordite, and to 890·5 c.c. for the 0·048-inch cordite, the volumes being, of course, taken at 0° Cent. and 760 mm. atmospheric pressure.

The heat generated was found to be:—For the earlier cordite, 1214 grm.-units water fluid; for the service 0·255-inch cordite, 1284 grm.-units water fluid or 1189 units water gaseous; for the service 0·048-inch cordite, 1272 units water fluid or 1178 units water gaseous.

From my very numerous experiments on erosion, I have arrived at the conclusion that the principal factors determining its amount are: (1) the actual temperature of the products of combustion, (2) the motion of these products. But little erosive effect is produced, even by the most erosive powders, in close vessels, or in those portions of the chambers of guns where the motion of the gas is feeble or *nil;* but the case is widely different where there is rapid motion of the gases at high densities. It is not difficult absolutely to retain without leakage the products of explosions at very high pressures, but if there be any appreciable escape before the gases are cooled, they instantly cut a way for themselves with astonishing rapidity, totally destroying the surfaces over or through which they pass. Among all the explosives with which I have experimented, I have found that where the heat developed is low, the erosive effect is also low.

With ordinary powders, the most erosive with which I am acquainted is that which, on account of other properties, is used for the battering charges of heavy guns: I refer to brown prismatic powder. The erosive effect of cordite, if considered in relation to the energy generated by the two explosives, is very slightly greater than that of brown prismatic; but very much higher effects can, if

it be so desired, be obtained with cordite, and, if the highest energy be demanded, the erosion will be proportionally greater. There is however, one curious and satisfactory peculiarity connected with erosion by cordite. Erosion produced by ordinary gunpowder has the most singular effect on the metal of the gun, eating out large holes, and forming long, rough grooves, resembling a ploughed field in miniature, and these grooves have, moreover, the unpleasant habit of being very apt to develop into cracks; but with cordite, so far as my experience goes, the erosion is of a very different character. The eddy holes and long grooves are absent, and the erosion appears to consist in a simple washing away of the surface of the steel barrel.

Cordite does not detonate; at least, although I have made far more experiments on detonation with this explosive than with any other, I have never succeeded in detonating it. With an explosive like cordite, capable of developing enormous pressures, it is, of course, easy, if the cordite be finely comminuted, to develop very high tensions, but, as I have already explained, a high pressure does not necessarily imply detonation.

The rapidity with which cordite gases lose their temperature, and consequently their pressure, by communication of their heat to their surrounding envelope, is very striking. Exploding a charge of about $1\frac{3}{4}$ lb. of cordite in a close vessel at a tension of a little over 6 tons on the square inch, or say 1000 atmospheres, I have found that the pressure of 6 tons per square inch was again reached in 0·07 second after explosion, of 5 tons in 0·171 second, of 4 tons in 0·731 second, of 3 tons in 1·764 second, of 2 tons in 3·523 seconds, and of 1 ton in 7·08 seconds. The loss of pressure after 1 ton per square inch was reached, was, of course, slow, but the figures I have given were closely approximated to in two subsequent experiments. With ordinary gunpowder the reduction of pressure was very much slower, as was to be expected, on account of the charge being much larger; on account, also, of the temperature of explosion being much lower.

These experiments are now being continued with larger charges and higher pressure.

It only remains to give particulars as to ballistics, that is, as to the velocities and energies realisable by cordite in the bore of a gun; but these will be most conveniently given with similar details regarding other explosives with which I have experimented.

The ballistite I have used has, like the cordite, been changed in composition since the commencement of my experiments. The sample I used for my earlier experiments was nearly exactly composed of 50 per cent of dinitro-cellulose (collodion cotton) and 50 per cent. of nitro-glycerine. The cubes were coated with graphite, and the nitro-cellulose was wholly soluble in ether alcohol.

The second sample was nominally composed of 60 per cent. of nitro-cellulose and 40 per cent. of nitro-glycerine. The proximate analysis gave—

Nitro-glycerine	41·62
Nitro-cellulose	59·05

as before the whole of the nitro-cellulose was soluble in ether alcohol.

The earlier sample gave the following permanent gases under pressures of 6 and 12 tons per square inch respectively:—

CO_2	37·3	38·49
CO	27·8	28·35
H	19·1	19·83
N	15·8	13·32
CH_4	traces.	

One gramme of this ballistite gives rise to 610 c.c. of permanent gases, and to 0·1588 grm. of aqueous vapour, corresponding to 197 c.c. at 0° Cent. and 760 mm.

Hence the total volume of gas is 807 c.c., and the heat generated by the explosion is 1365 grm.-units (water fluid), 1269 grm.-units (water gaseous).

Although I have not made nearly so many experiments on detonation with ballistite as with cordite, those I have made with the earlier samples (50 per cent. guncotton and 50 per cent. nitro-glycerine), neither detonated, nor did they show any tendency to detonate; but the case is different with respect to a sample of ballistite consisting of 60 per cent. guncotton and 40 per cent. nitro-glycerine. This sample, 0·2-inch cubes, detonated with great violence on two occasions; but I am unable, without further experience, to say whether this result was due to the change in the composition of the ballistite or to defective manufacture.

The erosive action of ballistite is, as might perhaps be anticipated

from the higher heat developed, greater than with cordite, but the remarks made with respect to the action of cordite apply also to ballistite.

The French B. N. powder consists of nitro-cellulose partially gelatinised and mixed with tannin, with barium, and potassium nitrates.

When exploded under a pressure of 6 tons per square inch, the permanent gases were found to consist of

CO_2	28·1 vols.
CO	32·4 ,,
H	21·9 ,,
N	16·8 ,,
CH_4	0·8 ,,

These permanent gases occupied at the usual temperature and pressure a volume of 616 c.c.; the aqueous vapour formed occupied in addition 206 c.c., so that the total gaseous volume was 822 c.c.

The heat generated was 1003 grm.-units (water fluid) or 902 grm.-units (water gaseous); the ballistics obtained with this powder are given along with those furnished by other explosives.

For purposes of comparison, I have introduced among the ballistic results those obtained with amide prismatic powder, and with R. L. G. Particulars as to both these powders have already been given * and need not here be repeated.

In a preliminary note, like the present, the most convenient mode of comparing the velocities and energies developed by the new explosives is by the aid of diagrams.

Accordingly, in Fig. 1 (coloured diagram, p. 480), I show the velocities of seven different explosives from the commencement of motion to the muzzle of the gun; the position of the points at which the velocity is determined are shown, and on the lowest and highest curves the observed velocities are marked where it is possible to do so without confusing the diagram. Lines are drawn to indicate the velocities that are obtained with the lengths of 40, 50, 75, and 100 calibres.

Fig. 2 (coloured diagram, p. 480) shows the pressures by which the velocities of Fig. 1 were obtained. The areas of these curves represent the energies realised, and the lines intersecting the curves indicate the pressures at which the gases are discharged from the muzzle for lengths of 40, 50, 75, and 100 calibres respectively. The

* *Roy. Soc. Proc.*, vol. lii., p. 125; *Phil. Trans.*, part i., 1880, p. 278.

chamber pressures indicated by crusher-gauges are also shown in Fig. 2, and it will be observed that the two modes of determining the maximum pressure are in general in close accordance.

It will further be observed that with the slow-burning powders the chronoscopic maximum pressures are somewhat, though not greatly higher, than are those indicated by the crusher-gauges. This observation is not new.* It was noted in the long series of experiments with black powders carried on by the Committee of Explosives.

The result is widely different where an explosive powder or a quickly-burning powder, such as R. L. G., giving rise to wave-pressure, is employed; the crusher-gauge in such cases † gives considerably and frequently very greatly higher pressures, and this peculiarity is illustrated in the curve from R. L. G. in Fig. 2.

It is, perhaps, hardly necessary to point out that the results given in Fig. 1 have to be considered in relation to the facts disclosed in Fig. 2. Thus it will be noted that the velocities and energies realised by 22 lbs. of 0·35-inch cordite and 20 lbs. of 0·3-inch cordite are practically the same; but reference to Fig. 2 shows that, with the 0·3-inch cordite, this velocity and energy has been obtained at the cost of nearly 30 per cent. higher maximum pressure.

A similar remark may be made in regard to the French B. N. powder if compared with the ballistite. Its velocity and energy are obtained at a high cost of maximum pressure, and it is interesting to note how the velocity curve of B. N., which for the first 4 feet of motion shows a velocity higher than that of any other explosive, successively crosses other curves, and gives at the muzzle a velocity of 500 feet per second under that of cordite.

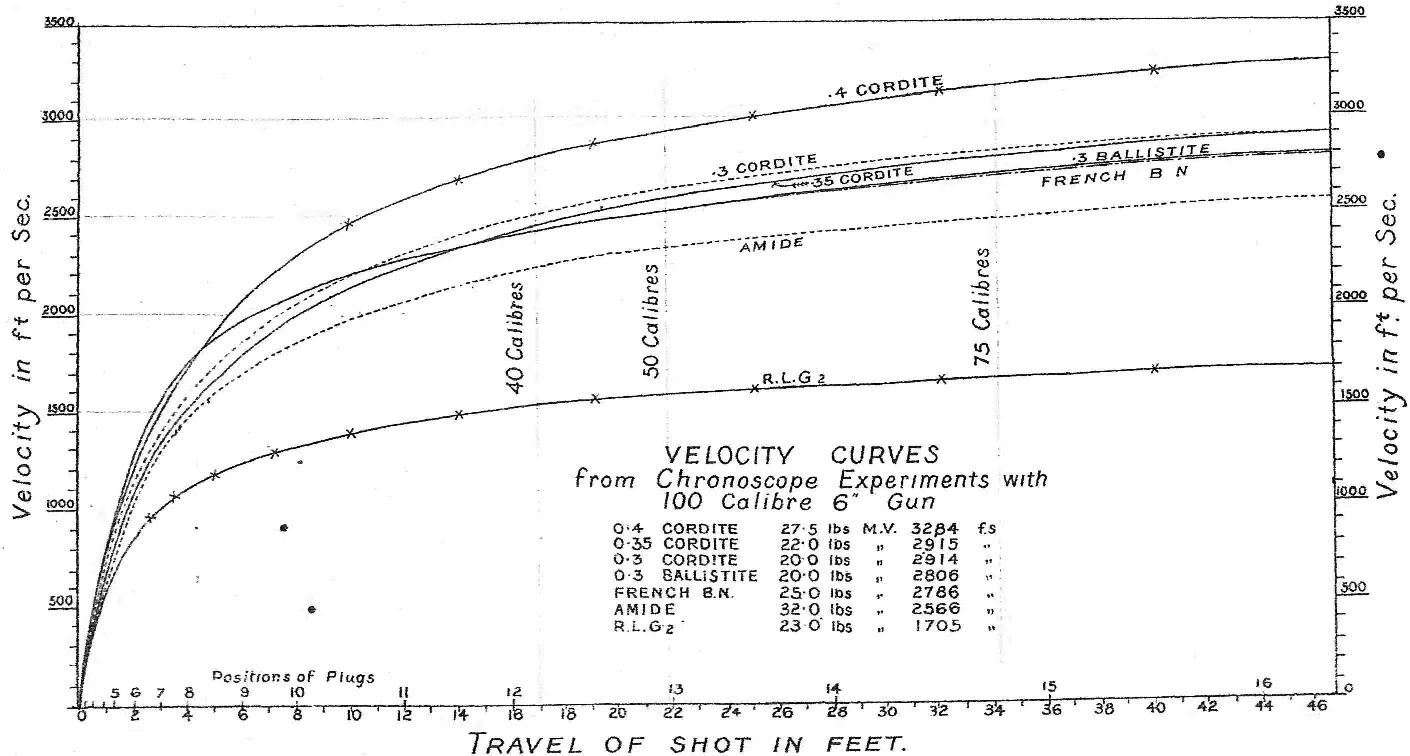
The velocities and energies at the principal points indicated in Figs. 1 and 2 are summarised in the annexed table, which shows for each nature of explosive the advantage in velocity and energy to be gained by correspondingly lengthening the gun.

Fig. 3 (coloured diagram) is an interesting illustration of a point to which I have elsewhere adverted. Cordite and ballistite leave no deposit in the bore. Round 1 with R. L. G. was fired with a clean bore. The difference in velocity between round 1 with a clean bore and rounds 2 and 3 with powder deposit in the chase, is very clearly marked, and it will be noted that in this instance the effect of the foul bore is only distinctly shown when the length exceeds 40 calibres.

* Noble and Abel, *Phil. Trans.*, vol. clxv., p. 110.

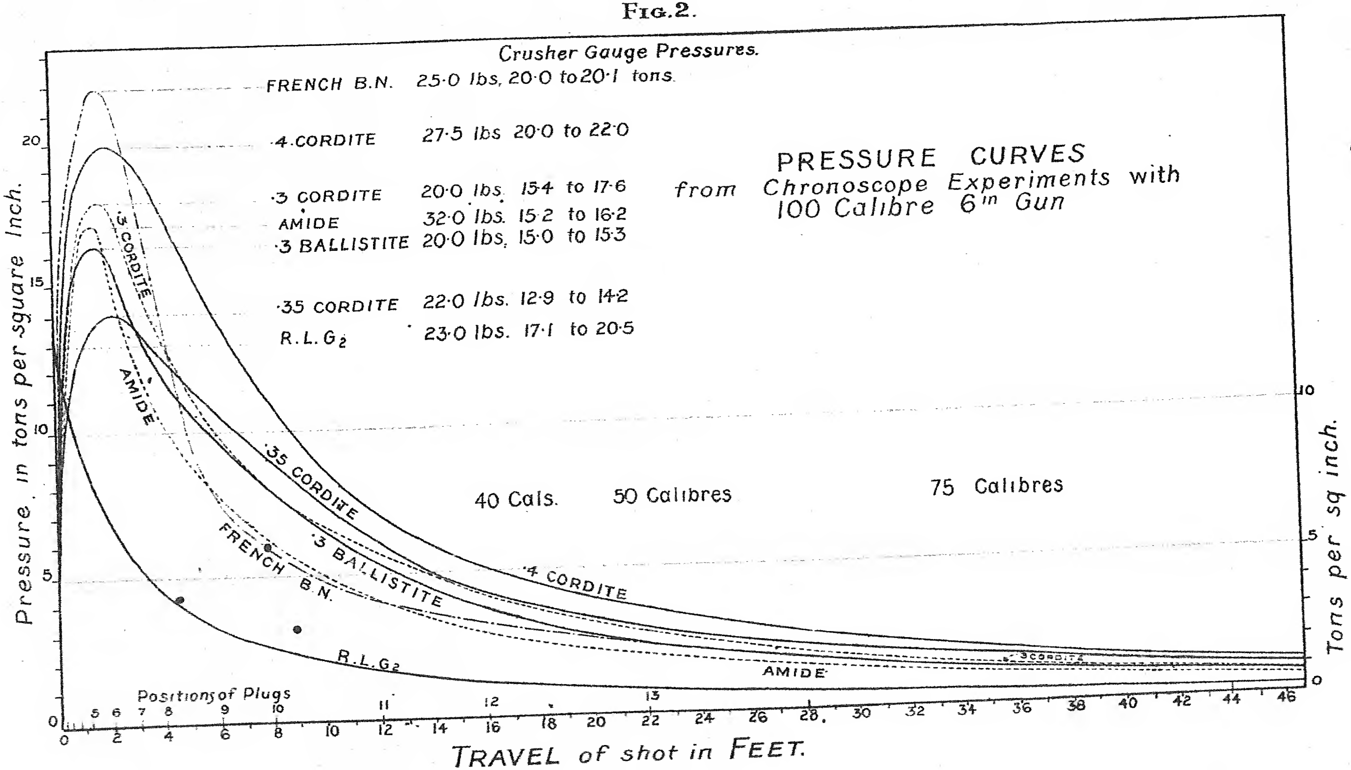
† Compare Noble and Abel, *loc. cit.*, p. 109.

FIG. I.



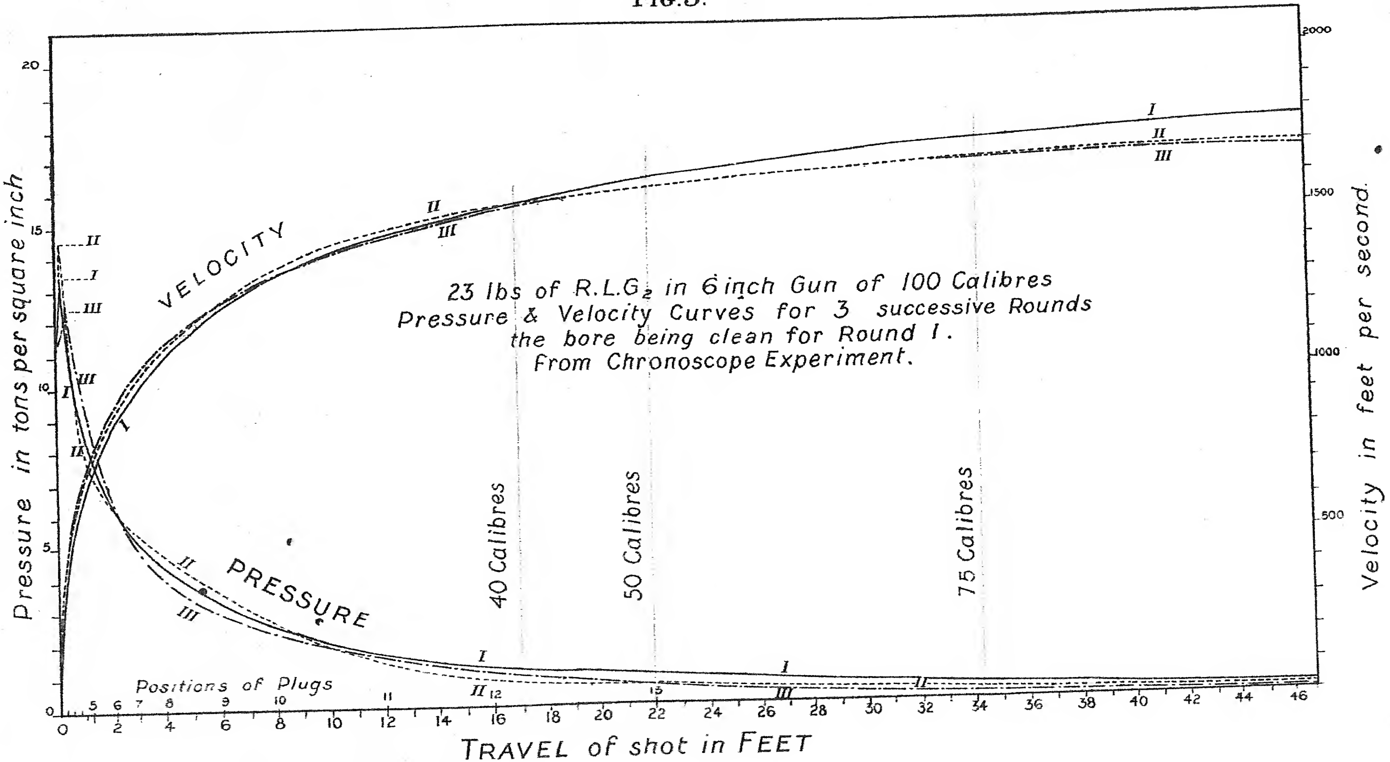
VELOCITY CURVES
from Chronoscope Experiments with
100 Calibre 6" Gun
0·4 CORDITE 27·5 lbs M.V. 3284 f.s
0·35 CORDITE 22·0 lbs " 2915 "
0·3 CORDITE 20·0 lbs " 2914 "
0·3 BALLISTITE 20·0 lbs " 2806 "
FRENCH B.N. 25·0 lbs " 2786 "
AMIDE 32·0 lbs " 2566 "
R.L.G2 23·0 lbs " 1705 "
·4 CORDITE
·3 CORDITE
·35 CORDITE
·3 BALLISTITE
FRENCH B N
AMIDE
R.L.G 2
40 Calibres
50 Calibres
75 Calibres
Positions of Plugs
Velocity in ft per Sec.
TRAVEL OF SHOT IN FEET.

Fig. 2.



Crusher Gauge Pressures.
FRENCH B.N. 25·0 lbs, 20·0 to 20·1 tons.
·4 CORDITE 27·5 lbs 20·0 to 22·0
·3 CORDITE 20·0 lbs. 15·4 to 17·6
AMIDE 32·0 lbs. 15·2 to 16·2
·3 BALLISTITE 20·0 lbs. 15·0 to 15·3
·35 CORDITE 22·0 lbs. 12·9 to 14·2
R.L.G2 23·0 lbs. 17·1 to 20·5
PRESSURE CURVES
from Chronoscope Experiments with
100 Calibre 6in Gun
40 Cals.
50 Calibres
75 Calibres
Pressure in tons per square Inch.
Tons per sq inch.
Positions of Plugs
TRAVEL of shot in FEET.
·35 CORDITE
·3 BALLISTITE
FRENCH B.N.
·4 CORDITE
·3 CORDITE
AMIDE
R.L.G2

FIG. 3.



Pressure in tons per square inch
Velocity in feet per second.
VELOCITY
PRESSURE
23 lbs of R.L.G₂ in 6 inch Gun of 100 Calibres
Pressure & Velocity Curves for 3 successive Rounds
the bore being clean for Round I.
From Chronoscope Experiment.
40 Calibres
50 Calibres
75 Calibres
Positions of Plugs
TRAVEL of shot in FEET

From 40 calibres onwards, the loss of velocity due to a bore encrusted with deposit is very distinctly shown.

TABLE 7.—*Showing the velocities and energies realised in 6-inch gun with the undernoted explosives.*

Nature of explosive and weight of charge.	Length of bore, 40 calibres.		Length of bore, 50 calibres.		Length of bore, 75 calibres.		Length of bore, 100 calibres.	
	Velocity.	Energy.	Velocity.	Energy.	Velocity.	Energy.	Velocity.	Energy.
Cordite, 0·4-in. dia., 27·5 lbs. . . .	2794	5413	2940	5994	3166	6950	3284	7478
Cordite, 0·35-in. dia., 22 lbs. . . .	2444	4142	2583	4626	2798	5429	2915	5892
Cordite, 0·3-in. dia., 20 lbs. . . .	2495	4316	2632	4804	2821	5518	2914	5888
Ballistite, 0·3-in. cubes, 20 lbs. . . .	2416	4047	2537	4463	2713	5104	2806	5460
French B.N., 25 lbs. .	2422	4068	2530	4438	2700	5055	2786	5382
Amide Prismatic, 32 lbs.	2225	3433	2331	3768	2486	4285	2566	4566
R. L. G.$_2$, 23 lbs. . .	1533	1630	1592	1757	1668	1929	1705	2016

XIII.

ON METHODS THAT HAVE BEEN ADOPTED FOR MEASURING PRESSURES IN THE BORES OF GUNS

(*Paper read before the British Association, Oxford,* 1894.)

THE importance of ascertaining, with some approach to accuracy, the pressures which are developed at various points along the bores of guns by gunpowder or other propelling agent is so great that a variety of means have been proposed for their determination, and I purpose, in this paper, to give a very brief account of some of these means, pointing out at the same time certain difficulties which have been experienced in their employment, and the errors to which these methods have been in many cases subject.

The earliest attempt, by direct experiment, to ascertain pressures developed by fired gunpowder, was that made by Count Rumford in his endeavour to determine the pressures due to different densities of charge. He assumed, the principles of thermo-dynamics being then unknown, that charges fired in a small closed gun-barrel would give pressures identical with those given by charges doing work both on the projectile and on the products of combustion themselves; but even this error was a small one compared with that which led him to adopt, as correct, his extravagant estimate of the pressures developed.

For a density of unity—or, in other words, for a charge approximately filling a chamber in which it was fired—he estimated the pressure at over 101,000 atmospheres, or at 662 tons per square inch.

He adopted this pressure notwithstanding the great discrepancy which he found to exist between the two series of experiments which he made, and he meets the objection that, were the pressure anything approaching that which he gives, no gun that ever was made would have a chance of standing, by assuming that the

combustion of powder is exceedingly slow, and lasts the whole time occupied by the projectile in passing through the bore.

It is sufficiently curious that a man so eminent for his scientific attainments as was Rumford should have fallen into so great an error, both because any attempt at calculation would have shown him his mistake, and because Robins, sixty years earlier, had conclusively proved that with the small-grain powders then used—and it must be remembered that Rumford's powder was sporting of very fine grain—the whole of the powder was fired before the bullet was very greatly removed from its seat. Robins's argument—and it is incontrovertible—was, that were it otherwise a much greater energy would be realised from the powder when the weight of the projectile was doubled, trebled, quadrupled, etc.; but his experiments showed that under these circumstances the work done by the powder was nearly the same.

For other objects, on a much larger scale, and with appliances far superior to those which the great man I have named had at his disposal, I have had occasion to repeat Robins's experiment, and the results are interesting. With a charge of 10 lbs. of the powder known as R. L. G. 2 and a shot weighing 30 lbs., a velocity of 2126 feet per second, representing an energy of 971·6 foot-tons, was attained. The same charge being used, but the weight of the projectile being doubled, the velocity was reduced to 1641 feet per second, while the energy was increased to 1125 foot-tons. With a shot weighing 120 lbs. the velocity was 1209 feet per second, and the energy 1196 foot-tons. With a shot of 150 lbs. the velocity was 1080 feet per second, and the energy 1191·5 foot-tons; while with a shot of 360 lbs. the velocity was reduced to 691 feet per second, representing a muzzle energy of 1191·9 foot-tons. These energies were obtained with maximum chamber pressures respectively of 13·5 tons, of 17·25 tons, of 19 tons, of 20 tons, and of 22 tons per square inch. It will be noted that the maximum energy obtained was realised with the shot of 120 lbs. weight, the energy given by a shot of 360 lbs.—*i.e.*, three times that weight, or twelve times the weight of the original shot—being nearly exactly the same.

Very different, however, were the results when one of the modern powders, introduced with the special object of insuring slow combustion, was compared with the R. L. G. 2 experiments which I have just quoted.

With brown prismatic or cocoa powder, an exactly similar series

was fired. The 30-lb. shot gave a velocity of 1515 feet per second, and an energy of 493·4 foot-tons; the 60-lb. shot gave 1291 feet per second, or an energy of 693·4 foot-tons; the 120-lb. shot, 1040 feet per second, or 877·5 foot-tons; the 150-lb. shot, 948 feet per second, and 920·7 foot-tons; while with the heaviest shot, the 360-lb., the velocity attained was 654 feet per second, equivalent to an energy of 1064·7 foot-tons. The maximum chamber pressures in this series varied from 4·8 tons per square inch with the lightest projectile, to 9·6, with the heaviest; and with this powder it will be observed that the energy developed increased steadily and considerably with each increment in the weight of the shot, while the low chamber pressure shows that, even with the heaviest shot, the projectile must have moved a considerable distance from its seat before the charge can be considered to have been entirely consumed.

I have mentioned the discrepancy between Rumford's two series of experiments. This discrepancy was very great, the one series giving, for a density of unity, a tension of about 190 tons per square inch, or 29,000 atmospheres, the other series giving a tension of over 101,000 atmospheres. It is remarkable that Rumford makes no attempt to explain this discrepancy, but, as he deliberately adopts the higher tension, it is not improbable that he was led to this conclusion by an erroneous estimate of the elastic force of the aqueous vapour contained in the powder or formed by its explosion. He considered, relying on M. de Betancourt's experiments, that the elasticity of steam is doubled by every addition of temperature equal to 30° Fahr., and his only difficulty appears to have been—he expressly leaves to posterity the solution of the problem—why the tension of fired gunpowder is not much higher than even the enormous pressure which his experiments appeared to indicate.

It will be remembered that Rumford's apparatus consisted of a small but strong wrought-iron barrel, terminated at one end by a small closed vent, so arranged that the charge could be fired by the application of a red-hot ball. At the other end it was closed by a hemisphere upon which any required weight could be placed. His method was as follows:—A given charge being placed in the bore, a weight judged to be equivalent to the expected gaseous pressure was applied. If the weight were lifted, it was increased until it was just sufficient to confine the gases, and the pressure was then assumed to be that represented by the weight.

It seems probable that Rumford's erroneous determinations were mainly due to two causes:—

1st. To the weight closing the barrel being lifted, not by the mere gaseous pressure, but by the products of explosion (produced, it will be remembered, from a very "brisante" powder, and considerably heated by the red-hot ball), being projected at a high velocity against it. In such a case, the energy acquired in traversing the barrel would add notably to the pressure due to the density of the charge; and it is again remarkable that the augmentation of pressure due to this cause was clearly indicated by an experiment designed for the purpose by Robins.

2nd. To the gases acting on a much larger area than was allowed for in his calculations; and this view appears to be confirmed by the *résumé* he gives of his experiments.

No attempt was made for very many years either to corroborate or amend Count Rumford's determinations; but, in 1845, General Cavalli endeavoured indirectly to arrive at the pressure developed by different kinds of powder in a gun of 16 cm. calibre. His method consisted in drilling holes in the gun at right angles to the axis, at different distances from the base of the bore, in which holes were screwed small barrels of wrought iron, so arranged as to throw a bullet which would be acted on by the charge of the gun while giving motion to the projectile. By ascertaining the velocities of these bullets he considered that the theoretical thickness of the metal at various points along the bore could be deduced. His experiments led him to some singular results.

He believed that with some very brisante Belgian powder with which he experimented a chamber pressure of 24,022 atmospheres (157·6 tons per square inch) had actually been reached, while with an ordinary powder and a realised energy of nearly the same amount the maximum chamber pressure was only 3734 atmospheres (24·5 tons per square inch). With the brisante powder this erroneous conclusion was doubtless due to two principal causes, viz.:—

1st. To the seat of the small bullet being at a considerable distance from the charge. Under these circumstances, as later on I shall have occasion to describe experiments to prove, a far higher pressure induces motion in the bullet than is due to the tension of the gases in a state of rest.

2nd. To the brisante nature of the powder. With such powders, especially in large charges, it has been proved that great variations of pressure exist in the powder chamber itself, in some cases the

pressure indicated at one point of the chamber being more than double that at others.

It has further been proved that with brisante powders waves of pressure of great violence sweep from one end of the chamber to the other, and if Cavalli's small bullet were acted on by one of these waves an exceedingly high pressure would, without doubt, be indicated.

3rd. A third cause of error, but much slighter, is due to the muzzle pressure, when the small bullet quits its barrel, being both abnormally high and also abnormally sustained; hence there will be a considerable increment of velocity after the bullet quits the gun.

It is but fair to add that the results obtained by Cavalli with the powders which he terms "inoffensive" are, if some correction be made for the third cause of error alluded to above, not far removed from the truth.

A Prussian Artillery Committee, under the presidency of General Neumann, made, in 1854, a great improvement on the plan proposed and employed by Cavalli.

Their mode of procedure consisted in drilling a hole in the powder chamber of the gun to be experimented with, in which hole was placed a small barrel of about 6 inches in length. Now when the gun was loaded, if in the small barrel were placed a cylinder of a length equal to that of the projectile, it is clear that, on the assumption that the pressure in the powder chamber is uniform, the cylinder and the projectile will describe equal spaces in equal times; hence, if we determine the velocity of the cylinder when it quits the small barrel, we know the velocity of the projectile when it has moved 6 inches from its seat. By altering the length of the column of the cylinder placed in the small barrel, and ascertaining the resultant velocity, the velocity of the projectile at any desired point of the bore can be determined.

General Neumann's Committee carried out their experiments only in very small guns and with the grained powder used in those days. Their results were probably not far from the truth, although subject to one of the defects to which I alluded in reviewing General Cavalli's experiments. Indeed, these results were examined and entirely confirmed by the distinguished Russian artillerist General Mayevski, in a very elaborate memoir; but the experiments of the Prussian Committee were chiefly remarkable for being, so far as I know, the first to recognise the variations of pressure which may exist in the powder chamber itself, variations which may, under

certain circumstances, attain great magnitude, and to which I have already drawn attention.

The results of the Prussian experiments showed, with every charge fired, two distinct maxima of tension. Other relative maxima no doubt existed, but the mode of experiment was not sufficiently delicate to render them perceptible.

Before passing to the more modern methods adopted for determining the tensions in guns, I must advert to one which has been repeatedly resorted to during the last one hundred and fifty years. I mean the method of firing the same weight of charge and projectile from guns of the same calibre but of different lengths, or, as has sometimes been done, by successively reducing the length of the same gun by cutting off a determinate number of calibres from the muzzle.

It is obvious that if, under the circumstances supposed, we know the muzzle velocities of a projectile from a gun of, say, 25 calibres in length and from a gun of 30 calibres in length, we are able from the increased energy obtained to deduce the mean pressure acting upon the projectile over the additional 5 calibres.

The earliest experiments with different lengths of guns appear to have been made in England as far back as 1736. These experiments, however, have but little value, as the velocities were not directly determined, and could only be deduced from the observed ranges. The same objection applies to the long series of experiments carried on in Hanover in 1785, and those cited by Piobert in 1801; but the interesting observation that the ranges obtained from guns of 12, 15, 19, and 23 calibres in length were relative maxima cannot be relied on in any way as showing abnormal variations in the muzzle pressure accompanying variations in length.

In Hutton's experiments, made with guns varying in length from 15 to 40 calibres, the muzzle velocities were obtained by means of the ballistic pendulum; and, between these limits of length, the mean powder-pressure he realised can with sufficient certainty be deduced.

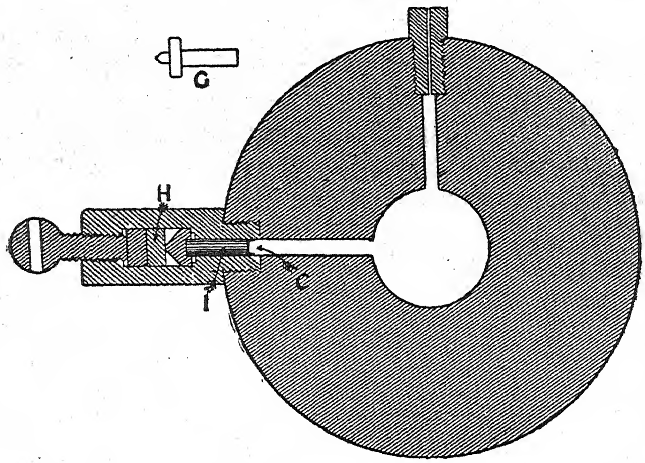
This remark applies also to the numerous similar experiments where the muzzle velocities have been obtained by the more accurate chronoscopes that have been for many years in common use; but this mode of determining the pressure has many inconveniences, and ceases to be reliable when the bore is of a very reduced length and the pressures approach their maximum value.

To the important and extensive series of experiments carried on by Major Rodman for the United States Government in 1857 to

1859, the main object of the experiments being to ascertain the effect which the size of grain of the powder used has upon the pressure, we are indebted for that officer's most ingenious pressure gauge; and the crusher gauge, which is now so extensively used, can only be considered a modification of Major Rodman's instrument designed to remove certain difficulties attending the use of the original instrument.

Major Rodman's gauge is well known, but its construction is

FIG. 1.—Rodman's Pressure Apparatus.



shown in the accompanying drawing (Fig. 1). Major Rodman applied his gauge in the following manner:—

Desiring to ascertain the pressure at various points along the bore of a gun, he bored at these points channels to the interior surface of the bore, and in these channels cylinders with small holes drilled down the centre were inserted; to this cylinder is fitted the indicating apparatus, carried by Major Rodman on the outside of the gun, and consisting of an indenting tool G with its knife (shown in elevation and section). Against the knife is screwed a piece of copper H. The pressure of the gas acting on the piston I forces the knife into the copper; by mechanical means a similar cut can be produced, and hence the magnitude of the cut gives the measure of the pressure which has produced it. A small cup at C prevents any gas passing the indenting tool.

The great improvements that Major Rodman made in gunpowder are well known. To him we are indebted both for the earliest experiments on the effect of the size of grain on the maximum

pressure and for the powder adopted by all nations for large guns, I mean prismatic powder; but it is a question whether he was not in some degree led to these great improvements by an erroneous estimate of the pressures produced, this erroneous estimate being mainly due to the necessity of placing the Rodman gauge at the exterior of the gun; and the effect of this objectionable position would be greatly exaggerated if the powder experimented with were of a "brisante" nature.

It is curious that so distinguished an artillerist as Major Rodman should never have taken the trouble to calculate what energies the pressures which his instrument gave would have generated in a projectile; had he done so he would have found that many of the results indicated by his instrument were not only improbable but were absolutely impossible.

As an illustration of Major Rodman's method I take an interesting series of experiments made in smooth-bored guns of 7-inch, 9-inch, and 11-inch calibres, and so arranged that in each gun an equal column or weight per square inch of powder was behind an equal column or weight per square inch of projectile. Under these conditions, in each gun, during the passage of the shot along the bore, the gases would be equally expanded, and the energy per unit of column developed at every point in the three guns should be the same, except for slight differences on account of increased temperature and pressure in the larger guns, due to the smaller cooling surface in proportion to the weight of charge.

Major Rodman measured his pressures at the base of the bore and at every 14 inches along it, and his results are given in the annexed table, which is a most instructive one:—

Diameter of Bore.	Weight of Charge in oz.	Weight of Shot in lbs.	Velocity.	Pressure at different Distances from Bottom of Bore in Tons per sq. in., at						
In.	Sq. in.	Sq. in.	F.S.	Bottom.	14 in.	28 in.	42 in.	56 in.	70 in.	84 in.
7	2·13	1·973	904	16·26	7·08	3·74	3·01	3·06	3·59	3·00
9	2·13	1·995	888	29·96	9·42	7·92	6·65	13·16	9·36	10·19
11	2·13	1·997	927	38·73	13·04	12·41	10·01	12·68	15·11	11·18

Examining this table, it will be observed, in the first place, that the muzzle velocities of the equal column projectiles are nearly the same; that of the 11-inch gun being, as it should be, somewhat the higher; hence the energies per square inch must be nearly the same,

and the mean pressures per square inch, inducing these energies, must likewise be the same.

But, for example, comparing the 7-inch and the 11-inch guns, it will be noted that in the latter gun the pressures are always twice and sometimes more than four times as great as in the 7-inch gun, the mean pressure being nearly three times as great.

The energy should be in the same proportion; hence, if the pressure observations had been correct, the observed velocity should have been 1570 feet per second, instead of 927 feet per second.

It will be noted also that the forward pressures not only differ greatly in the several calibres, but, for instance, in the 9-inch gun the pressure at 56 inches from the bottom of the bore is double the indicated pressure measured at 42 inches. Rodman accepts the pressures up to and including 42 inches as correct, but ascribes the irregular pressures in the chase to the vibrations of the metal due to the discharge.

Some experiments made by the earlier Explosive Committee fully explain the cause of the differences between the pressures exhibited by the 7-inch and 11-inch guns.

In the first of the experiments of this Committee, they used simultaneously Rodman's gauge and the chronoscope to which I shall presently advert. In the former case, of course, the pressure was determined directly. In the latter it was deduced from the motion communicated to the projectile. The results were quite irreconcilable, as a few examples will show.

In an 8-inch gun, with a charge of 32 lbs. of Russian prismatic powder and a projectile of 180 lbs. weight, fired from a vent a little in advance of the centre of the charge, and called the forward vent, the chronoscope gave a maximum pressure of 20·4 tons, while the Rodman gauge gave maximum pressures in the powder chamber varying from 26·7 to 33·7 tons per square inch. In the same gun, under similar conditions, a similar charge of pellet powder gave, with the chronoscope, a maximum pressure of 19·2 tons per square inch, while the chamber pressures given by the Rodman gauge varied from 41·6 tons to 49·2 tons per square inch.

But perhaps more striking discrepancies were exhibited by two series of experiments with R. L. G. of Waltham-Abbey make, fired from the same gun, and developing in the projectile approximately the same energies. In the first of these series, with a charge of 20 lbs. red from a forward vent, the maximum chronoscope pressure was

13·3 tons, while the Rodman gauge gave pressures varying from 24·6 to 38·9 tons per square inch.

In the second series, all conditions being the same, except that the charge was fired from the extreme rear, the maximum chronoscope pressure was 14·3 tons, while the Rodman pressure varied from 31·6 tons per square inch to over 50 tons per square inch, that pressure being the highest which the instrument was capable of registering, every observation in this series with the gauge placed at the seat of the shot being over fifty tons.

Shortly afterwards the Rodman gauges were destroyed, two of them being blown from the gun.

These discrepancies led the Committee to investigate with certain powders the variation in pressure indicated when a guage was placed at the surface of the bore and at the exterior of the gun, as with the Rodman gauge.

For this purpose they used the crusher-gauge, which admits of being placed in both positions.

With pebble-powder the gauge placed at the interior of the bore gave 14·5 tons; placed under precisely the same conditions at the exterior it gave 27 tons per square inch. With R. L. G. the similar figures were respectively 20 and 57 tons, and with L. G. respectively 19·5 and 45·5 tons per square inch.

The error I have just discussed was due to the position of the gauge; but Rodman's pressures and the pressures of the Explosive Committee were exaggerated from another cause. It will be readily understood that if a pressure of, say, 20 tons per square inch be suddenly applied to a gauge, and if the resistance to the motion of the knife be initially trifling, a certain amount of energy will be communicated to the piston and knife; and the copper when measured will indicate not only the gaseous pressure, but in addition a pressure corresponding to the energy impressed upon the piston during its motion.

This cause of error can, however, be eliminated by producing beforehand by mechanical means a cut indicating a pressure a little less than that to be expected.

Rodman admits that his chase pressures are erroneous; their exaggeration is no doubt greatly due to the causes I have just pointed out; but in my opinion, based upon long experience, no gauge of this description placed in the chase, where the products of explosion are moving with a very high velocity, can be depended upon to give reliable results.

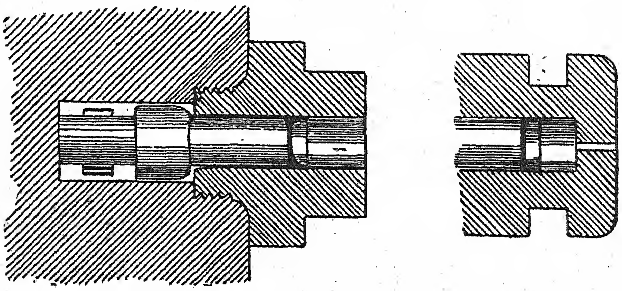
If we disregard the energy of the moving products and suppose the gauge to be acted on by pure gaseous pressure, with a projectile moving at the rate of 2500 feet per second (and such velocities are now quite within the range of practical ballistics), the projectile would pass the entrance to the Rodman gauge in something like the $\frac{1}{100000}$th part of a second. It is difficult to imagine that the full indentation could be given to the copper in this small fraction of time, and, if it were not so given, the gauge would indicate the pressure at a point considerably in advance of the gauge.

On the other hand, if, as would generally be the case, the products of explosion moving at a high velocity acted on the piston, the energy of these products would be reconverted into pressure, and the gauge would in this case give too high a result.

Major Rodman appears to have considered it impossible that any gauge could rightly indicate a pressure higher than that indicated by another nearer to the seat of the shot. This, however, is not so; nothing is more certain than that, with the powders known as "Poudres brutales," and, possibly, in a less degree with all explosives, motion is communicated to the shot by a series of waves or impulses; and it is easy to see that, if the position of a gauge coincided with the "hollow" of a wave, while that of a more forward gauge coincided with the "crest," the latter might easily show the higher pressure. Later on I shall revert to this point.

The crusher-gauge is a modification of the Rodman gauge, designed to overcome some of the defects of that instrument, and it is now

Fig. 2.—Crusher-Gauge.



almost universally used for the direct measurement of pressure: it is shown in the diagram exhibited (Fig. 2), and its action is easily understood. The powder gases act upon the base of the piston, compressing the copper cylinder; the amount of crush on the cylinder serves as an index to the maximum tension acting on the piston. It

is usual, where possible, to employ in each experiment two or three gauges so as to check the accuracy of the determination. Properly used, very great confidence may be placed in their results; but, as may be gathered from my remarks on the Rodman gauge, this and all similar gauges will cease to give reliable information as to the energy that can be impressed on a projectile, or as to the mean pressure on the surface of the bore, if there be any probability of the products of explosion being projected into them at a high velocity. In such a case the pressure indicated would not be the true gaseous pressure, such as, for instance, would exist were the products of ignition retained in a vessel impervious to heat until the waves of pressure generated by the explosion had subsided. But I defer an examination of the results given by the crusher-gauge until I compare these results with those given by the indirect method of deducing the pressure from the motion of the projectile within the bore.

The method I have adopted for this purpose consists in registering the times at which a projectile passes certain fixed points in the bore of a gun. The chronoscope (Figs. 3 and 4, p. 498), which I have designed for this purpose has been so often described that I shall only here briefly allude to it. It consists of a series of thin discs made to rotate at a very high and uniform velocity through a train of geared wheels. The speed with which the circumference of the discs travels is between 1200 and 1300 inches per second, and, since by means of a vernier we are able to divide the inch into thousandths, the instrument is capable of recording the millionth part of a second.

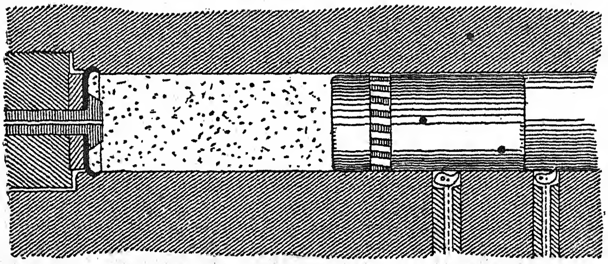
The precise rate of the discs' rotation is ascertained from one of the intermediate shafts, which, by means of a relay, registers the revolution on a subsidiary chronoscope, on which, also by a relay, a chronometer registers seconds. The subsidiary chronoscope can be read to about the $\frac{1}{5000}$th part of a second.

The registration of the passage of the shot across any of the fixed points in the bore is effected by the severance of the primary of an induction coil causing a spark from the secondary, which writes its record on prepared paper gummed to the periphery of the disc. The time is thus registered every round at sixteen points of the bore.

In the earlier experiments with this instrument the primary was cut by means of the arrangement shown in Fig. 5, and this was entirely satisfactory when velocities of from 1400 to 1600 feet per second were in question. But with the very high velocities now employed, with velocities, for example, between 2500 and 3500 feet

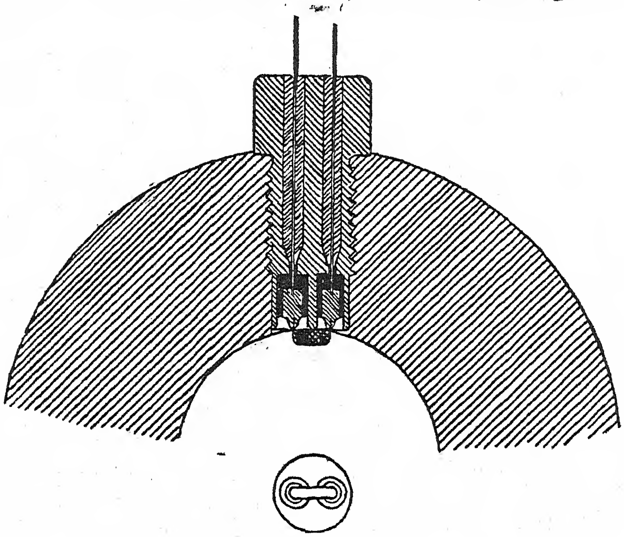
per second, the knife, instead of being knocked down, frequently cuts a long groove in the cast-iron projectile, on some occasions reaching the driving band of the shot before being forced into its place.

FIG. 5.—Original Apparatus for Cutting Wire by Moving Shot.



On account of this defect I have in all recent experiments adopted the arrangement shown in Fig. 6, which gives extremely satisfactory results, if care be taken that the plug is sufficiently secured to

FIG. 6.—Improved Apparatus for Cutting Wire by Moving Shot.



prevent its being forced out of its place by the rush of compressed air displaced by the passage of a projectile.

I have ascertained by experiments which I need not here describe that the mean instrumental error of this chronoscope, due chiefly to the deflection of the spark, amounts only to about three one-millionths of a second.

I must not conceal the fact that the determination of the pressure by this method is attended with very great labour. As an illustration I have prepared a diagram (Fig. 7, p. 498) of a recent set of experiments. Usually the pressures are deduced from the mean of three consecutive rounds fired under the same circumstances.

In this case, owing to the bore being clean, a much higher velocity was obtained from the first round, and the velocities and pressures were therefore calculated both for the mean and independently for each of the three rounds.

The first curves represented in the diagram are the time curves. So far as the eye can see, the time curves in all cases pass through the observed points. From the time curves the velocity curves are deduced, and I have given for each velocity curve the observed velocities, so that the accordance of the computed curve with the observed velocities will be seen. The velocity curve being fixed, the pressure curve of necessity follows, and the diagram shows both the accordance of the two rounds fired under the same circumstances and the slight discordance in the forward part of the curve of the round with the bore clean is very distinctly shown.

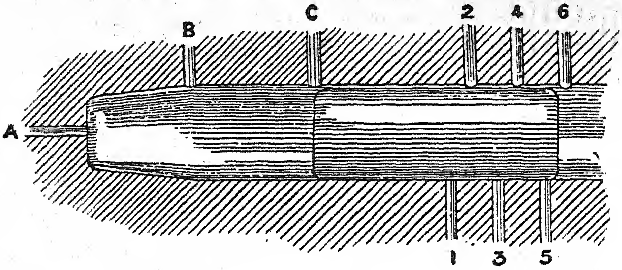
Comparing now the methods of determining the pressures which have been chiefly used in this country—I mean the chronoscope and the crusher-gauge—if the object sought be merely to determine the maximum pressure developed with the powders now generally in use, no instrument can be simpler than the crusher-gauge, and, when properly used, its indications may be taken as very approximately correct, but it cannot be relied on to give accurate results when placed in positions where the products of explosion are moving with a high velocity.

The maximum pressures under the conditions I have supposed are very approximately confirmed by the chronoscope, as may be seen by comparing the pressures shown on the diagram giving the results as to pressure obtained with certain new explosives, to which I shall presently advert. As a general rule, it may be said that, where the powders are slow in lighting and no wave action exists, the chronoscope pressures are generally somewhat higher than those of the crusher-gauge; but the case is very different where the powder is of a highly explosive or quick-burning description. With such powders, not only are the crusher-gauge pressures greatly above those of the chronoscope, but the widest difference frequently exists between the pressures indicated in different parts of the chamber in the same experiment. The

pressures, moreover, are often greatly above those which would exist were the charge absolutely confined in a close vessel.

A very striking instance may be cited from the early experiments of the Explosives Committee with a M. L. 10-inch gun (Fig. 8). The first round was fired with a charge of 87½ lbs. Belgian Pebble, the charge being lighted in two places. The maximum pressure with the chronoscope was 25·2 tons. With the crusher-gauge the pressure in the chamber varied from 22·2 to 24·8 tons per square inch, while the energy developed by the powder on the shot was 6240 foot-tons. With the second round, all conditions being the same except that the charge was fired at a single point, the chronoscope pressure was as nearly as possible the same; but the chamber pressure was, at the rear, 79·1 tons; in the middle, 52·0 tons; at the seat of the shot, 39·5 and 48·0 tons per square inch.

FIG. 8.—Position of Pressure Plugs in 10 inch Gun.



A similar large excess of pressure was shown at points 1 foot and 2 feet in advance of the seat of the shot, and the crusher-gauges did not show their normal pressures until points 5 or 6 feet from the seat of the shot had been reached.

Yet with the violent difference in pressure shown between the crusher-gauges in this round and in the previous round (which I have just cited), the difference of energy developed in the shot was exceedingly trifling, being only 6249 foot-tons, as against 6240.

I believe I have expressed pretty clearly my views that crusher-gauges placed in the chase are for absolute determination not of much value, and their main use, if used at all, is to give comparative results. But the same remark does not apply to crusher-gauges placed in the chamber.

Gases moving at a high velocity in the chase are, so to speak, performing their proper function; but the same is not true of those

violent waves of pressure in the chamber which appear to accompany the explosion of all brisante powders, and which occur either when the projectile has hardly moved at all or when it is moving with a comparatively slow velocity.

It is our object, and in this we have had great success, to avoid these waves as much as possible; and in attaining this end our indebtedness to the crusher-gauge is very great, as this instrument has made plain to us not only the extreme violence but the variability of these oscillations.

I have heard it urged that these waves of pressure are, after all, not of high importance, because their maxima act at the same time only upon a very small section of the bore, and the continuity of the metal is amply sufficient to resist the stress.

This is no doubt true, but it is not true of the base of the bore, which in modern guns is almost invariably a movable piece, and which under certain circumstances might have to sustain the full force of the violent pressures, a sample of which I have cited.

To ascertain the mean pressure throughout the bore, it seems to me that there is no method so satisfactory, despite its attendant labour, as that of making the projectile write its own story. In that case we cannot fall into the error of making the pressures three or four times as great as are necessary to generate the energy the projectile has actually acquired, while occasional errors, due to causes I have not time to explain, are easily detected and eliminated.

To give an idea of how great is the range of velocity over which these experiments have been carried, I exhibit here diagrams (Figs. 9 and 10, p. 498) showing the velocities and pressures obtained with several of the new explosives which in recent years have attracted so much attention. Observe also how closely, with the exception of the one somewhat brisante powder, the results given by the chronoscope accord with those given by the crusher-gauge. Where these differ, as I have elsewhere pointed out, the two modes of research so widely different are complementary to each other.

The chronoscope takes little or no note of the violent oscillations of pressure acting during exceedingly minute intervals of time. On the other hand, if with the explosives I allude to we trusted to the indications of the crusher-gauge, we should arrive at a most erroneous idea of the energy communicated to the projectile.

In concluding, if I may venture to quote the excuse of a much more eminent man than myself, I have only to express my regret

that I have not had time to condense the remarks with which I fear I have fatigued you, while at the same time I am aware that there are many important points in connection with my subject which I have left altogether untouched, and others upon which I have touched that require further elucidation.

FIG. 3.—Chronoscope Plan.

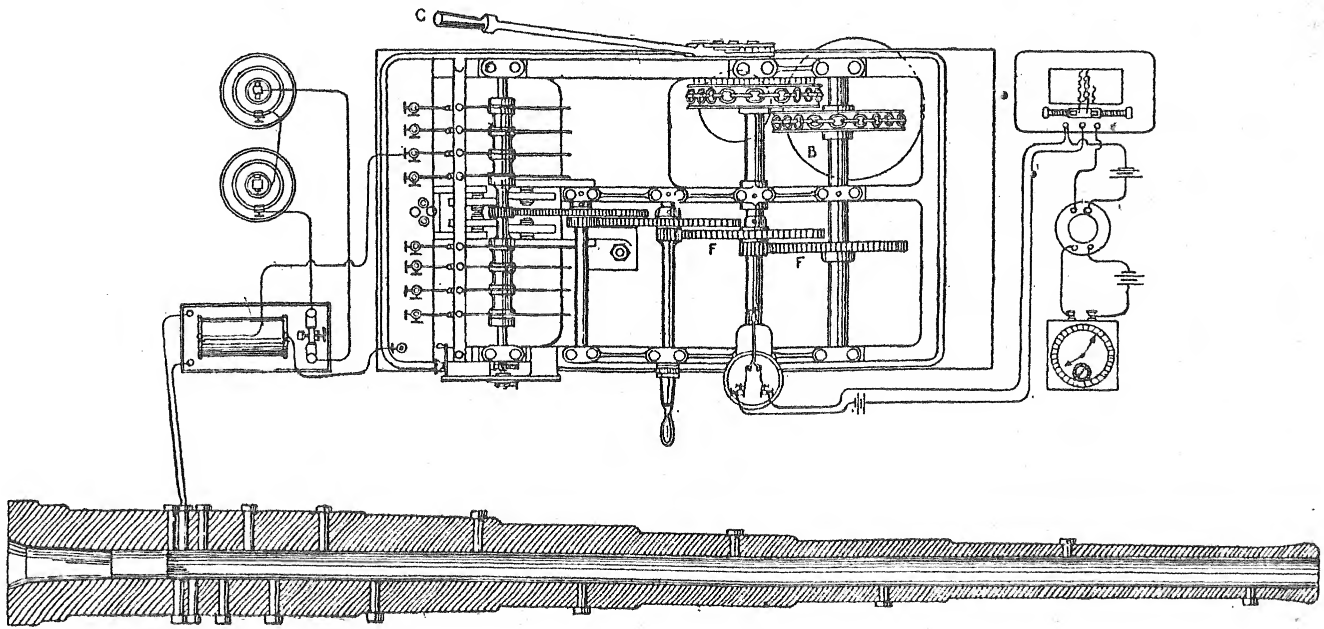


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Fig. 4.—Chronoscope Elevation.

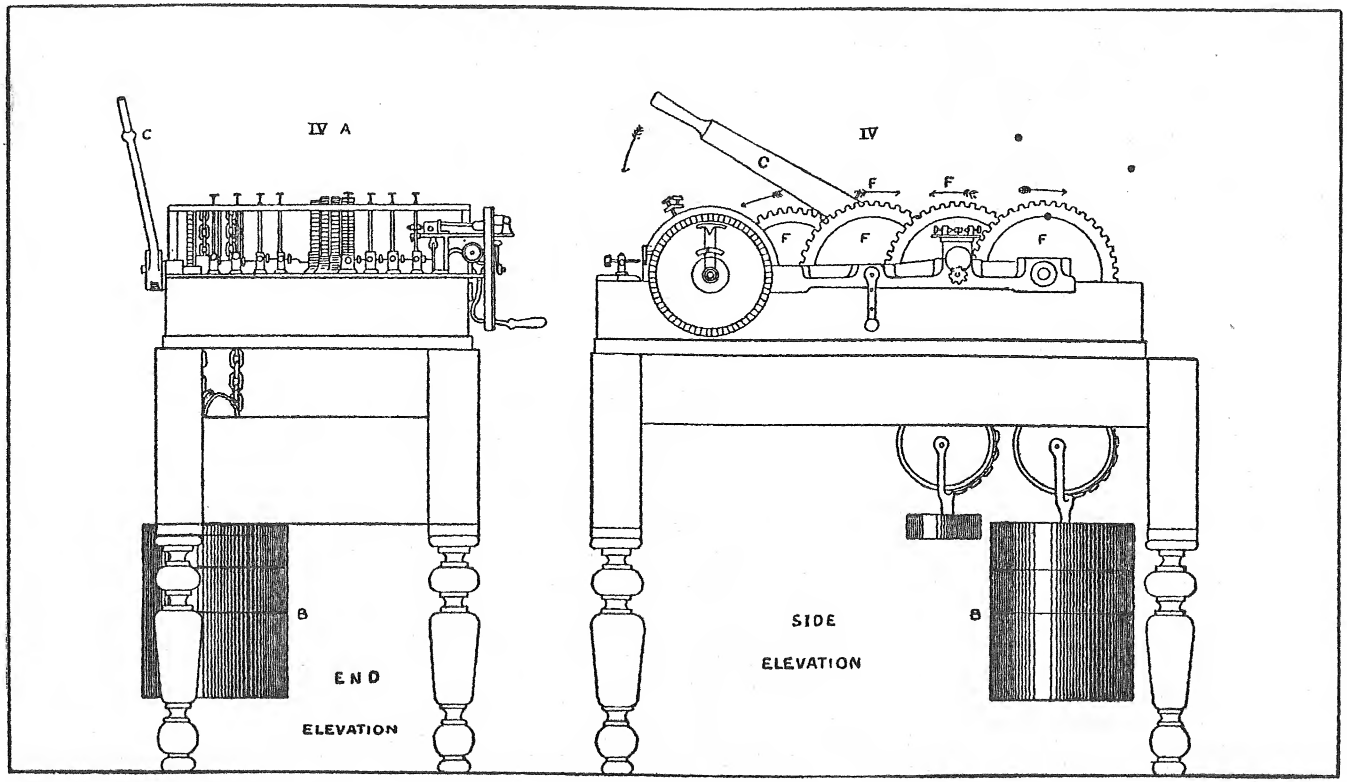

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FIG. 7.—Chronoscope Observations from 6-inch 100-calibre Gun, 23 lb., R.L.G.2, and 100-lb. Projectile.

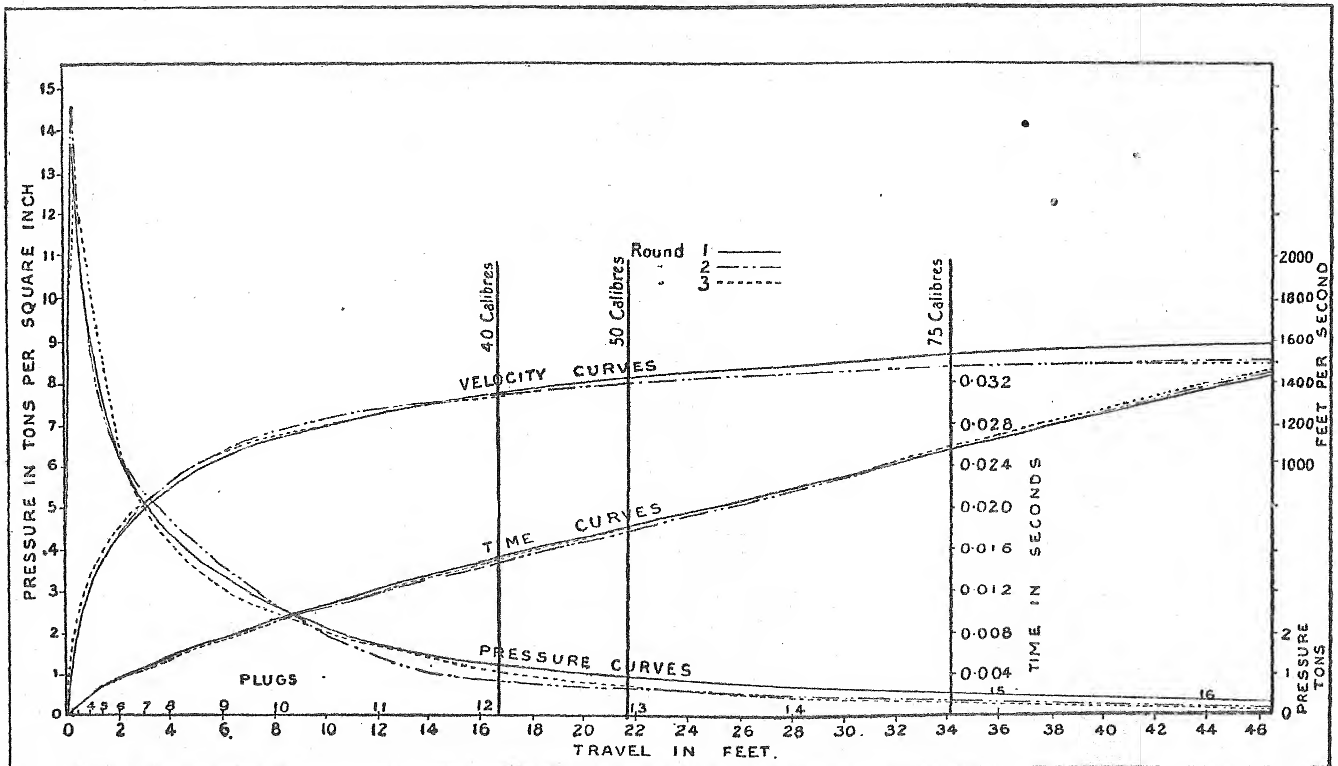

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FIG. 9.—Chronoscope Velocity Curves, 6-inch 100-calibre Gun.

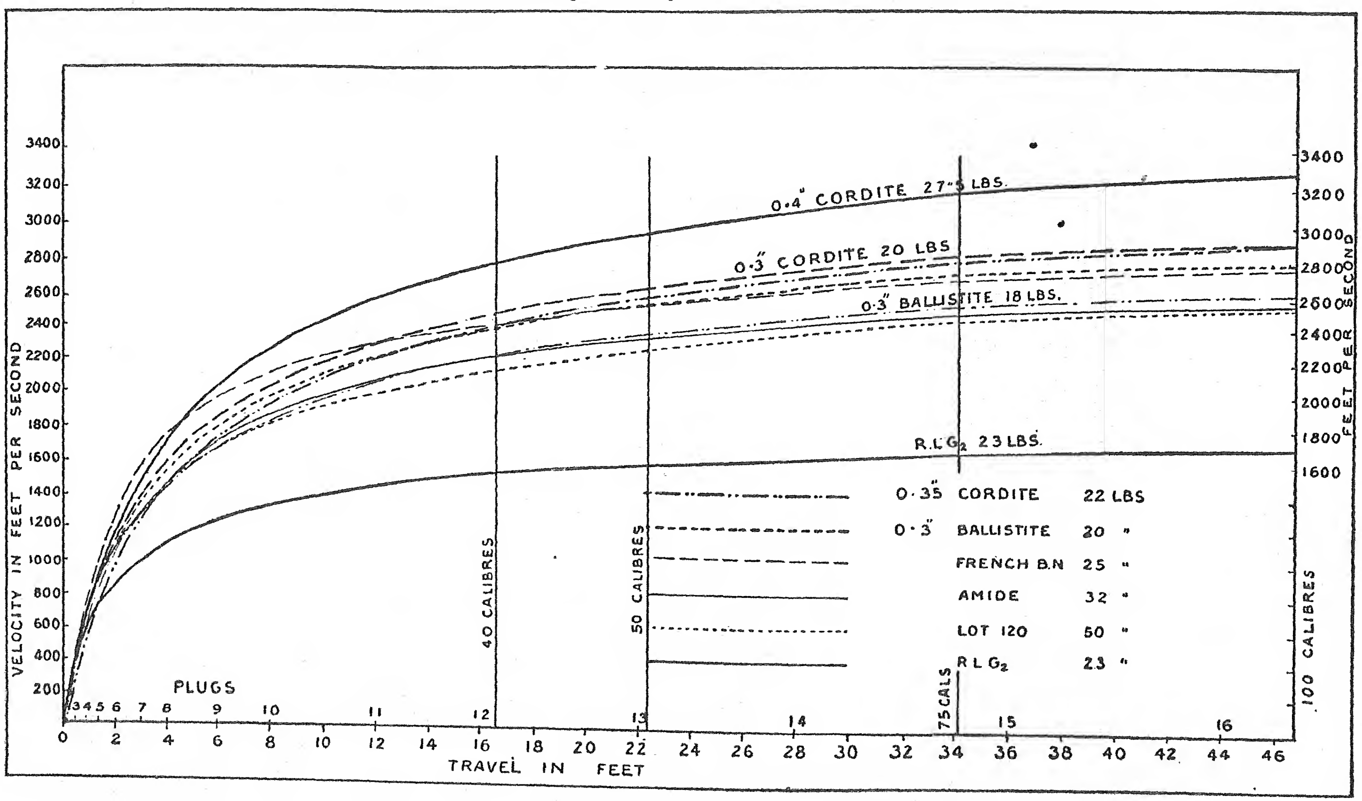

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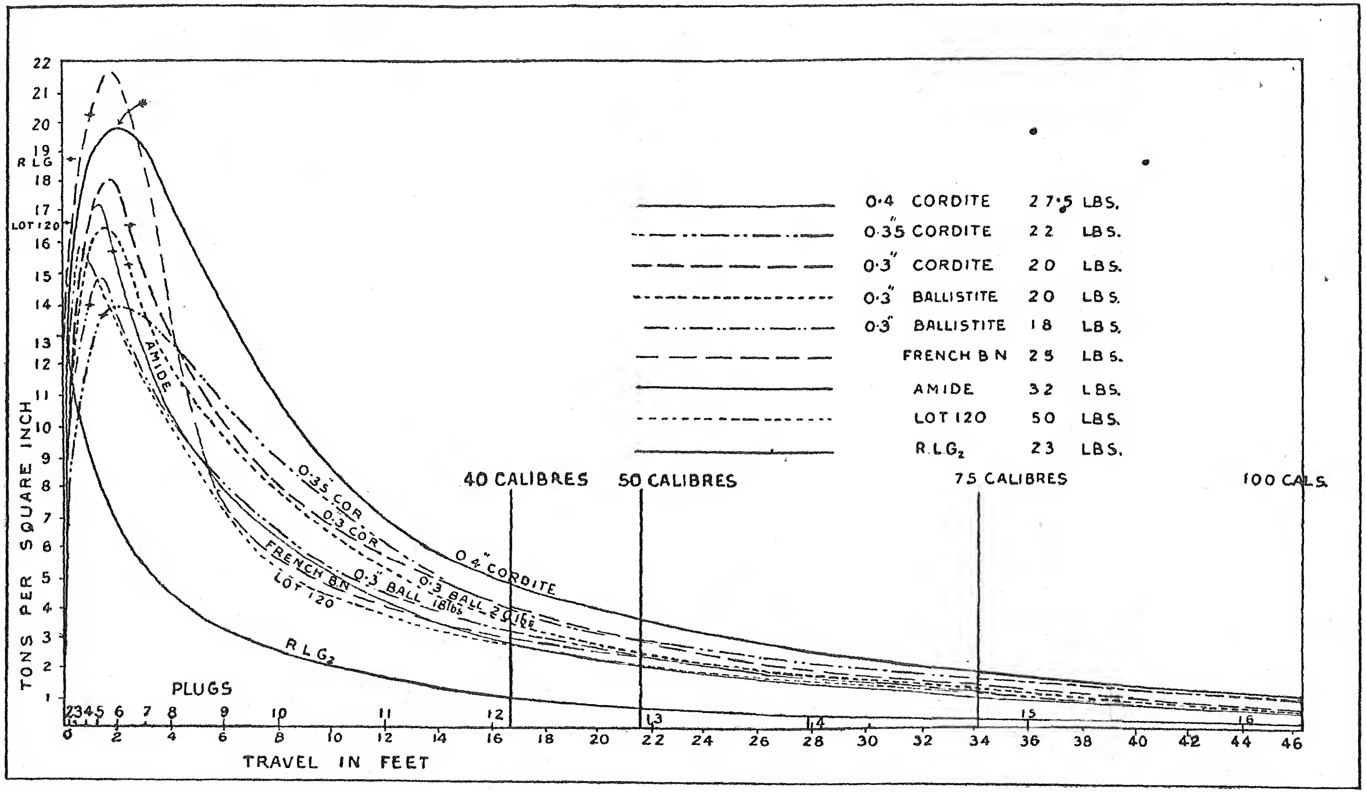
FIG. 10.—Chronoscope Pressure Curves, 100-calibre 6-inch Gun.



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XIV.

THE RISE AND PROGRESS OF RIFLED NAVAL ARTILLERY

(*Paper read at the Institution of Naval Architects, Newcastle-upon-Tyne,* 1899.)

AT the last meeting which the Institution of Naval Architects held in this city, an invaluable paper by Lord Armstrong and Mr Vavasseur was read and discussed, and it appears to me that, using this paper as a landmark, it may be convenient, and not uninteresting, to give a brief sketch of the subject of my paper during the fifty years of my connection with artillery, and to note the striking progress which artillery science, in common with other applied sciences, has made during the last years of the century now drawing to a close.

In the paper to which I have referred, Lord Armstrong and Mr Vavasseur draw attention to the primitive carriages on which the guns of the first half of the present century were mounted; but the guns themselves were nearly as primitive, differing in little, except in size and power, from those with which the fleet which met the Great Armada were armed.

It is both interesting and instructive to compare the guns which in 1850 formed the principal armament of the most powerful frigates or line-of-battle ships, with the guns which now form the principal secondary armament of first-class cruisers and battleships.

In the year I have mentioned, and it will be remembered that within a short period the long peace which succeeded the Napoleonic wars was broken, the principal guns with which our ships were armed were 32-prs. They were, we must admit, of very rude construction, mere blocks of cast iron, the sole machining spent upon them being the formation of the bore and the drilling of the vent.

The velocity of the shot was about 1600 feet per second, and the energy developed in it by the charge was about 570 foot-tons.

The carriage upon which this rude gun was mounted was even more rude. It was made, as described by Lord Armstrong and Mr Vavasseur, entirely of wood; generally, in later years, of teak or mahogany. It was carried on wooden trucks, or sometimes the rear trucks were replaced by a chock. The recoil was controlled by the friction of abnormally large wooden axles, and sometimes by wedges acting on the trucks, and was finally brought up by the breeching by which the gun was attached to the vessel's side. The elevation was fixed by quoins resting on a quoin bed, and handspikes were used either for training or for elevating. For the running out, at the date I have mentioned, blocks and tackle were generally employed.

To work, with any degree of smartness, such rude weapons, a very strong gun's crew was necessary, and, indeed, the gun and its carriage were absolutely surrounded by its crew. For the sake of the younger members present, who may probably not have seen the weapons I have been describing, I show in Plate I.* (p. 520), a 32-pr. gun of H.M.S. *Excellent*, with its crew at practice.

In the year 1858 the first great step in artillery progress was made. In that year the Committee on Rifled Cannon recommended the introduction of the rifled Armstrong guns into the service, and the experiments which were made with these and other rifled guns opened the eyes of all who gave attention to the subject to the great advantages possessed by the new artillery.

With regard to range, accuracy, and penetrative power, the superiority of rifled guns was so conspicuous that nearly all artillerists were at once convinced that the days of smooth-bored guns were numbered. The advantage in range at high angles of elevation at first excited some surprise, as the velocity of the projectile was, from causes to which I shall later advert, very much lower than in the case of the smooth-bored guns.

Comparing, for example, the velocities and energies of the 32-pr. smooth bores, to which I have adverted, and the 40-pr. R. B. L. guns, which, on the introduction of rifled guns replaced them, the comparative muzzle-velocities were respectively 1600 and 1200 feet per second, and the comparative muzzle-energies respectively 570 and 400 foot-tons. It is hardly necessary to point out that at comparatively short distances the superiority of the rifled gun, both in regard to range and penetration, manifested itself.

* From Sir Howard Douglas's *Naval Gunnery.*

But in these early days of rifled artillery, the point which attracted most attention was the great increase of accuracy. The writer, in using the method of "Least Squares" to determine the relative accuracy of rifled and smooth-bored guns of approximately the same weight, showed that, at a range of 1000 yards, half the shot fired from a rifled gun fell in a rectangle of about 23 yards long by 1 yard wide, while in the case of the smooth bore the similar rectangle was about 145 yards long by 10 yards broad.

The objection to the use of iron and steel as a material for carriages was shown by careful experiment to be founded on prejudice, and the introduction of iron carriages has been so fully described in the paper by Lord Armstrong and Mr Vavasseur that I need not here further refer to it.

I have alluded to the reduction in velocity of projectiles fired from rifled guns when these weapons were first introduced, and this reduction arose from two causes. First, because the flatness of the trajectory and increased penetrative power of rifled projectiles at long ranges were at first supposed to be sufficient; and, secondly, because the numerous failures of rifled guns, with the materials and modes of construction then in vogue, rendered artillerists cautious as to the stresses to which rifled guns, especially those with deep grooves, were subjected.

But the battle between guns and armour rendered it a matter of first-rate importance to increase the potential energy of our rifled guns, and the first steps in this direction were made by the Explosives Committee, who, by their experiments, showed that, with improved forms of powder, the velocities, which had generally run between 1200 and 1300 feet per second, could, in the same guns, be raised to 1600 feet per second, the increase in velocity being at the same time accompanied by a very considerable reduction of maximum pressure.

But perhaps the most important step was made by my firm, who, acting upon certain experiments carried out at Elswick, and which formed the subject of memoirs by myself and Sir F. Abel, made, in 1877, 6-inch and 8-inch guns, with which, while the maximum pressures remained the same, the velocities of the rifled projectiles were at a single bound raised from 1600 to 2100 feet per second, thereby increasing the energies by nearly 75 per cent., and immediately another reconstruction of guns and their mountings became a necessity.

At the same time, from the increase in the length of guns, which

the slow-burning powders and high energies then introduced demanded, a return to breech-loading from the somewhat retrograde change to muzzle-loading, which had some years before been adopted, was also necessitated.

Nearly all these breech-loading guns were arranged for velocities somewhere about 2000 feet per second, the mountings also were greatly improved; but it is unnecessary for me here further to allude to these improvements, as they have been fully described in the paper by Lord Armstrong and Mr Vavasseur, to which I have so often referred.

At about the date of that paper, however, experiments were being made in three directions, the whole of which experiments were destined to have a most important bearing on the progress of naval artillery. The first of these had reference to the question as to whether gunpowder, which had since the days of Roger Bacon, that is for nearly seven centuries, no serious competitor as a propelling agent for artillery purposes, was to retain its pre-eminence.

The second was due to my own initiative. Seeing the great advantages that had attended the introduction of the small rifled guns designed by Hotchkiss and Nordenfeldt, my firm had constructed 4·7-inch and 6-inch quick-firing guns, and submitted them to the Admiralty. The success of these guns, both in our own and in foreign navies, was rapid and complete; and it is not too much to say that, for cruisers and the secondary armaments of battleships, their adoption amounted to another reconstruction of artillery.

The third series of experiments were on the question of the introduction of high explosives as bursting charges for shell—a question of great importance, both in an artillery point of view, and as affecting naval construction.

With reference to the first of these questions, it is unnecesary to tell you that the long pre-eminence of gunpowder has come to an end. In this country, for artillery purposes, it has been replaced by the cordite of Sir F. Abel and Professor Dewar, and this explosive has also been used extensively abroad. Many other nations employ ballistite or kindred explosives, giving results generally similar, but having a somewhat less potential energy. Having spent many years in experimenting on gunpowder, I cannot quit that interesting subject without regret; but, as I have also experimented largely with cordite and other kindred agents, I am obliged to confess that the new explosives have many and great advantages. The absence of smoke, and an increase of energy, with the same maximum

chamber pressure, of about 50 per cent., are advantages much too great to be overlooked. There is one point, however, to which I ought to allude, and which is, I believe, at present exercising the minds of the authorities to a considerable extent. I mean the rapid destruction of the bores due to the erosion by cordite. It must be borne in mind, however, that if taken in relation to the energy developed, the erosion of cordite differs but little from that of brown prismatic powder, which is also very erosive, and gives rise to erosion of a much more objectionable character. Erosion is, in my opinion, caused by three factors—the heat of combustion, the pressure, and the motion of the products of combustion—not to any chemical action. This view is borne out, not only by my numerous experiments on this subject, but by the state of the surface of close vessels in which large charges have been fired, and by the examination of the chambers of guns from which a large number of charges have been fired.

In the forward part of the chamber, where the gases are in rapid motion, the erosion is decided; but in the rear of the chamber, where the temperature and pressure are highest and longest continued, but where there is little or no motion, there is no trace of erosion. Let, however, but a slight leakage past the pad occur, and the effects of erosion are immediate and decided.

The object, then, at which we have to aim is to diminish the temperature of explosion, and I am not without hopes that this greatly-to-be-desired end may before long be achieved.

The velocities obtainable with cordite are very high. There would be no difficulty, should it be desired, in approximating with ordinary projectiles to 3000 feet per second; but, for many reasons, I consider very high velocities objectionable, and, if a given energy be required, would prefer to see it represented by a lower velocity. I may here mention that, with a 100-calibre 6-inch gun, and with a projectile of the dimensions of the ordinary 6-inch projectile, but of aluminium, I have obtained a muzzle velocity of close upon 5000 feet per second.

Turning now to the quick-firing guns, I think it will be most convenient to consider the guns themselves in connection with their mountings; because these last, when rapidity of fire is in question, are quite as important as the arrangements of the guns themselves.

Early in the year 1887, the gun and mounting shown in Plates IV. and V. (p. 520) were submitted for trial on board H.M.S. *Handy*. The gun was the first mounted on the Elswick cradle, having the

recoil-press and spring box beneath the cradle, the piston rods and the attachments for compressing the springs during recoil being fixed to a horn on the gun. The weight of the gun and mounting was taken on balls under the pivot, and the mounting and shield were carefully balanced. The whole weight of the gun and mounting was about 4 tons 12 cwt., and it could be trained quite easily by the shoulder, no gear being used. The sights were placed on the cradle, and did not recoil with the gun. No. 1 could with ease train with the shoulder-piece, work the elevating gear, lay, and fire by means of an electric pistol. During the operation he was quite clear of the breech, and could keep the gun pointed continuously on the object.

With this gun and mounting a very great advance in rapidity of fire was obtained. The breech mechanism was of the three-motion type, and was very quick and handy; but the great speed was obtained by the careful design of both gun and mounting, in such a manner that the movements of one did not interfere with those of the other. At the trial above mentioned ten rounds were fired in 47½ seconds, and later as many as fifteen rounds per minute were obtained. An interesting incident connected with this gun and mounting may be mentioned. The gunboat *Mastiff* was ordered to fire ten rounds as rapidly as possible from her service 5-inch B. L. gun. The time taken for the ten rounds was 6 minutes 16 seconds, so that the quick-firing gun fired its ten rounds before the then service gun fired its second shot.

About the same time a great improvement was made in the mode of mounting of the smaller 3-pr. and 6-pr. quick-firing guns. Up to that date they were mounted on crinoline, or so-called elastic, stands; but, with this pattern, the strains on the decks and holding-down bolts were very severe. The mounting shown in Plates VI. and VII. (p. 520), in which the gun recoils in the line of fire, was submitted for trial at Portsmouth, and proved itself so successful that it was at once adopted in our own and many other navies.

In 1890 an important improvement in quick-firing mountings was introduced, viz., the pedestal mounting shown in Plates VIII. and IX. (p. 520). The cradle is of the same type as that of the 4·7-inch quick-firing gun above mentioned. The carriage is of forged steel in the form of a "Y," having a long shank which fits into the pedestal and forms the pivot. The whole weight is taken on the end of the pivot, and the mounting can be trained with ease by a few pounds applied at the shoulder-piece. The pedestal is very solid, is of forged steel, and affords excellent protection to the pivot; the base is also

small, and, there being no rollers or roller-paths, the deck may be considerably distorted without interfering with the working of the piece.

The shield is of a very substantial character, 3 inches thick, and perfectly balanced; it is attached to the carriage by means of flexible stays, so arranged that, if the shield be struck, the stays yield, and a very reduced shock is transmitted to the carriage.

This mounting was the first to be fitted with the bar and drum sight, also shown on Plates VIII. and IX. (p. 520).

In 1891 an experimental mounting of this type was made for a 4·7-inch gun. It was fitted with a 3-inch shield with sloping roof, carried by yielding stays, and with this mounting a firing trial was carried on to compare its resistance to injury with that of a centre pivot roller-path mounting, in which a shield 3 inches thick formed an integral portion of the mounting, which had in addition an outer shield 1¼-inch thick. The latter mounting was disabled after two rounds, one each from a 3-pr. and a 6-pr. This trial showed conclusively that steel castings, although giving excellent tests, could not withstand a severe blow from a projectile. The pedestal mounting received no less than twelve rounds before it was disabled, four from a 3-pr., six from a 6-pr., and two from a 4·7-inch gun; and it would not then have been disabled, had the pedestal been made, as they are now, of forged steel. In the experimental mounting the pedestal was of plate and angle; the last projectile fired penetrated the pedestal and jammed the pivot. Even then the damage was not serious, and could have been rectified in a few hours, but with this exception, the mounting in all other respects was as good as ever.

This type of mounting for guns up to 6-inch calibre is now almost universal in our own and many other services.

In Plates X. and XI. (p. 520) are shown a 6-inch mounting of the latest type as arranged for a casemate between decks. It differs chiefly from those previously described in having training gear fitted on both sides, and in having a special arrangement made for removing the balls which form the bearing at the base of the pivot from the side instead of from below. A small jack is provided to take the weight of the gun and mounting, and in a few minutes the balls can be removed, examined, and replaced. The arrangements permit the gun to be elevated through the whole angle of 22° in 11 seconds, and to be trained through the whole angle of 120° in 16 seconds by one man.

An important improvement in the cradles for 6-inch and larger mountings was the result of a trade dispute. In 1894 a strike of

moulders took place. The cradles up to that date had been made of cast steel, and, as at Elswick, considerably more than 100 mountings were stopped for want of cradles, it was determined to substitute forged for cast steel. A new design was consequently made, and a much more satisfactory cradle, lighter and more reliable, was produced. At Elswick cast-steel cradles are not now made, unless specially ordered.

I am now in a condition to make the comparison referred to in the opening sentences of this paper. In Plate III. (p. 520), I have placed side by side diagrams of the 6·3-inch 32-pr. of 1850 and of the 6-inch 100-pr. of the present day, while Plates I. and II. (p. 520) show the crews necessary to work the guns. You will observe the diagrams give the pressures, velocities, and energies of the two guns. The velocity and energy given by the 32-pr. are, respectively, about 1600 feet per second and 570 foot-tons. The corresponding figures for the 6-inch Q. F. are 2570 feet per second and 4580 foot-tons. But the rapidity of fire and accuracy of the modern gun are even more remarkable.

Most of you are doubtless aware of the conditions under which target practice is carried on in the navy. Each gun's crew has 3 minutes to fire as many rounds as they can with accuracy, the variable range commencing at about 2200 yards, diminishing to about 1600 yards, and again increasing to 2200 yards. In H.M.S. *Blake* the best gun's crew fired eighteen rounds, hitting the target fifteen times, while the total number of rounds fired by her ten guns was one hundred and forty-eight, the target being hit one hundred and ten times. H.M.S. *Royal Arthur* did nearly as well, the best gun having fired eighteen rounds, striking the target fourteen times.

In Plates XII. and XIII. (p. 520) are shown two systems of dismounting gear for 6-inch guns. The bogie system is used for the upper deck, or for casemates where it is not necessary to run the gun back for stowing. It is only used for purposes of examination, and is found to be very convenient. One pair of bogies is usually supplied per ship.

The between deck dismounting gear is shown on the same plate. It consists of a lever L mounted on rollers on an overhead rail, which can be run backwards or forwards by means of an endless chain on a sprocket wheel, worked by means of worm gear and hand chain as illustrated. The lever L is readily attached to the cradle at about the centre of gravity, and the screw J to the breech end. Then, by means of the capstan head, the lever L takes the weight of the gun, and gun and cradle are run back together, rested on chocks, and secured as shown. This system of dismounting gear has been

rendered necessary from the great projection of the muzzle when guns are mounted on the broadside, due to the length of the guns. The time occupied from commencement to "gun secured" is about 4 minutes, and from casting loose to gun in firing position, about 3 minutes.

The above arrangement is that now in the service, but a new design has recently been made, fitted up, and experimentally tried at Elswick. From the results of these experiments, it seems probable that the above times will be reduced to something between a half and a third of those I have mentioned.

Plates XIV. and XV. (p. 520) show an 8-inch C. P. mounting for swift cruisers. The man at the sights can look over the top of the shield, thus commanding a good field of view, his head being protected by a hood. Electric and auxiliary hand training gear is provided, either of which can be applied at once, should the other be disabled. The elevating gear is worked entirely by hand, the trunnions being mounted on Mr Brankston's anti-friction arrangement, with knife edges supported on springs to relieve the shock when the gun is fired.

So easily does this gear work, that one man can elevate or depress the gun at the rate of 2° per second. With the hand training gear one man can train the mounting through 60° in 25 seconds, and with the electric gear through 180° in 30 seconds. The shield is 4½ inches thick, and is supported on elastic stays in the usual manner. The powder-supply is brought up the centre, and is delivered at the side under cover of the shield. The axial hoist for this purpose is shown in Plate XVI. (p. 520), and is so arranged that, when one charge is going up, the empty case is going down, thus effecting a great saving of time and labour, as the weight of the two cases balance each other, and there is thus only the actual weight of the charge to lift. Four rounds have been fired in a minute from this gun.

In 1889 Mr Vavasseur and the writer submitted to the Admiralty the design of a mounting so arranged that the gun could be fired at all elevations up to 35° or 40°, the firm having been requested by a foreign government to consider whether or not such an arrangement was feasible.

The naval authorities were much pleased with the design: but, as the arrangement was altogether novel, it was not unreasonably stipulated that, before it could be introduced into the service, its success must be proved by an experimental mounting being made, and by passing a satisfactory firing trial.

My firm agreed to the stipulation, and a high angle mounting for

a 9·2-inch gun was made at Elswick at the firm's expense, and fitted up in the *Handy*. It passed a most satisfactory firing trial in April 1890.

The total weight of the gun and mounting was 54 tons, and it could be trained quite easily by hand power. The gun had a range of elevation from 5° depression to 40° elevation, and an arc of 45° could be traversed in 30 seconds by one man. At the trial, rounds were fired at angles varying from 5° depression to 39° elevation, and the results were most satisfactory. The range of three of the rounds at 39° was estimated to be about 10 miles, but the shot could not be seen to strike the water.

In this mounting the slide was horizontal, and the carriage was of the Vavasseur type, the recoil-press and carriage being in one piece of forged steel; the gun consequently, did not recoil in the line of fire, but horizontally, and was returned to the firing position by means of springs, the force of the springs being regulated by means of a controlling ram in the recoil-press. Illustrations of this type of mounting are shown in Plates XVII. and XVIII. (p. 520). A considerable number of vessels, chiefly in foreign navies, are fitted with this form of mounting.

Plates XIX. and XX. (p. 520) show the type of armoured gunhouse arranged for the very powerful Chilian cruiser *O'Higgins*. This mounting affords excellent protection to the gun's crew, having 8-inch armour in front, and 5-inch on the sides and rear; the trunk for the supply of cartridges being also protected by 5-inch armour. The gun and mounting can be trained either by electric gear or by hand power. A store of projectiles is carried in the gunhouse for ready supply. The cordite charges come up the central trunk by means of a hydraulic motor; arrangements are also provided for bringing shell up this trunk to replace the ready supply.

Plates XXI. and XXII. (p. 520) show the type of twin-armoured gunhouses supplied to several Japanese cruisers. The following points may be mentioned. The training gear can be worked by hydraulic, electric, or hand power. Sighting gear for both guns is supplied to both sighting stations, and the mountings can be trained, and both guns elevated or depressed, from either station. A good supply of projectiles is carried in the gunhouse (30 per gun), and an electric bollard is provided to enable this supply to be replaced. The cordite is supplied through a central trunk, protected by an armoured barbette.

The armour of the gunhouse is attached to the turntable by means of elastic stays.

Before passing to the arrangements connected with the guns, which form the principal armament of battleships, I may mention a discussion which illustrates in a striking manner how widely separated are the ideas held by those who now rule the Queen's Navy and by those who held a similar position forty years ago. About that time I was secretary to a long-forgotten committee, called the "Committee on Plates and Guns," and among the subjects discussed was the design of a rifled gun of 7 tons weight. The naval authorities, however, were very strong in insisting that no gun weighing more than 6 tons could be safely carried on board ship, and I believe that the weight selected for that extraordinary weapon called the "Somerset Gun" was due to a compromise between the weights I have mentioned.

Turning now to guns of larger calibre, I propose to draw attention to some of the designs of the last twelve years. At the beginning of this period was designed the *Re Umberto*, with two barbettes, each having a pair of 13½-inch 68-ton guns. The mounting of these guns is principally noteworthy, because of two features which have again come to the front in more recent ships, viz.: what is known as all-round loading of the guns, which, in the *Re Umberto*, were protected by a circular barbette, and the provision of what is known as a working chamber below the turntable, into which depend, from the rear of the gun, hoists which are charged from this working chamber, the charges being first brought up by a central hoist terminating at the floor of the working chamber. As will be seen from Plates XXIII. and XXIV. (p. 520), the guns had trunnions, partly in order that they might be also available for land service. They were exactly balanced on these trunnions, in order to reduce the work of elevating and depressing the guns (which in this design is entirely done by hand) to a minimum; that is, so far as the work of lifting weight is concerned.

To reduce the work of overcoming the friction of the trunnions, a special device is placed under the trunnion of the gun between the plates of each cheek of the carriage. It consists of the arcs S, supported on the spring T, Plate XXIV. (p. 520). The springs are made powerful enough to lift, say, 98 per cent. of the weight of the gun, so that, although the gun is not thereby lifted off the usual trunnion bearing in the carriage, the majority of the weight is transferred to the rolling surface of the arc U, and to its point at W, where the knife-edge friction is insignificant. The recoil-presses are made on the Vavasseur principle. The piston rods pass out of their cylinders

at opposite ends, and are attached to the gun slides, so that one may be used as a means of running the gun out, and the other be used for running it in. The hydraulic pressure for this purpose is passed to and from the cylinders by means of a passage drilled up the centre of each piston rod, so that the connection of the hydraulic system is only made to that end of each cylinder which never receives a high recoil pressure.

The ammunition hoists behind the gun are carried upon the centre girder of the turntable to which their guides are attached. The powder-tube is inclined at the loading angle, and is partially blocked up at its bottom end, so that the powder when passed into it may not slide too far through. The powder-charge, delivered by the central hoist, is passed over by hand in separate parts to this tube.

The shot trough is also fixed at the loading angle, and is pivoted, so that it may be slung round to receive the shot from the central hoist.

The cylinders for working these ammunition hoists are telescopic, the smallest ram having insufficient power to lift the powder and shot, so that it is not till after the shot is rammed into the gun that the hoist has power to lift the cage to the height required for ramming the powder home.

The breech mechanism is hydraulic, and is carried in the turntable within the protection of the armour, so that, although the guns, as will be noticed, are almost entirely exposed, there is no very vulnerable part about them.

The central ammunition hoist passes up from the shell-room and magazine passages to the battery through an armoured tube. The cage is almost cylindrical, and is provided with a turntable top.

Before sending the hoist down to receive the charge, it is necessary to turn this table top into one particular position, and this position will present the shell and powder receptacles in the correct direction for charging the hoist down below.

If, when the hoist comes up with the charge, it is found that the gun is so trained that the rear hoist is not in line with the centre hoist, the turntable top can be revolved to the proper position, and if the gun turntable is in motion the hoists can be locked together while the shot is passed through from one to the other.

The trial of this mounting took place on 26th April 1893, and later on those of the *Sicilia* and *Sardinia*, which were of the same design.

Six ships of the *Royal Sovereign* class had their guns mounted in oval barbettes with one fixed loading station. These guns also were

almost entirely devoid of armoured protection. Then came the desire to have a second or alternative station for loading, together with breech mechanism carried on the gun, and armoured shields protecting as much of the guns as possible, which found expression in the design shown on Plates XXV. and XXVI. (p. 520).

This design, like some of the earlier ones, had a single fixed loading station, but had an important alteration to the hydraulic loading rammers. These were made with a trough, attached to and moving with the second, or larger, ram.

The ammunition cage, instead of coming up between the rammer and the gun, was placed alongside the rammer, so that the shot and powder charges could readily be rolled out into the trough carried by the rammer. Moreover, as this trough advances towards the gun it acts as a locking bolt to secure the gun turntable in position, and then to secure the gun-slide in position, and finally it bridges over the breech-screw threads in the gun.

The smaller ram of the rammer next advances, pushing the charge from the trough into the gun. This arrangement removed all fear of damage to the rammer by movement of the ammunition cage, training of the turret, or depressing the gun.

For the alternative method of loading, the gun was placed in line with another hydraulic rammer fitted at the rear end of the gun shield where space was allowed for a small chamber, giving room to work projectiles from a small bin to a trough in line with the rammer.

This loading gear can, of course, be used in any position of training of the guns.

A concurrent advantage of the shield is that the sighting hoods are placed well above the guns, thereby giving a better all-round view. At the same time, however, it should be noted that the men at the guns are not so well protected, and there is a possibility that they may suffer from small projectiles entering at the gun ports.

The ships fitted according to this design are seven, of the *Majestic* class, also the Japanese ships *Fugi* and *Yashima.* The last five of the *Majestic* class might have been fitted with all-round main loading positions, had it not been, I believe, that the frames for the oval barbettes were well advanced, and it was feared that any alteration of design might cause delay.

The *Canopus* mounting, designed at Openshaw, was therefore the first for the English Admiralty to be carried out with all-round loading.

I regret that time has not allowed me to have lithograph drawings

of this prepared. The chief feature is the provision of a roomy working chamber below the gun turntable, into which the powder and projectiles are brought by suitable central hoists. These hoists are fixed in relation to the ship. In order to transfer the shot to the gun hoists, hydraulic cranes are fitted.

Also in the working chamber there are shell bins holding twenty-four rounds per gun, which are also commanded by the hydraulic cranes, and these shell bins could all be exhausted first, and be replenished by the central hoists at leisure.

There is no doubt some disadvantage in having two sets of hoists, the central ones and those behind the gun, as it involves an additional set of operations to transfer the charges from one to the other; but against this must be set the fact that, having a large store of projectiles immediately under the gun turntable, an ordinary action might be fought before this store could be used up, so that the central hoists might never be required for use during the action. We have indeed brought forward the idea that, by still further increasing the storage of shell below the turntable, the provision of central shot hoists and shell-rooms at the bottom of the ship would be unnecessary.

I am assured by my colleague, Mr Watts, the Chief Constructor at Elswick, that, although it might not be possible to carry out this idea in existing ships, there would be no difficulty in designing a ship to meet this requirement, and I would point out that there would be a considerable total saving of weight if the central hoists and the shell-room gear could thereby be dispensed with. This is, perhaps, particularly observable in the next 12-inch design to which I now draw your attention, and which is shown on Plates XXVII., XXVIII., and XXIX. (p. 520).

This mounting is fitted with a pair of main hoists, each carrying a projectile and powder-charge from the bottom of the ship to the rear of the guns. It also has, as an alternative, a pair of shot hoists reaching from the bottom of the ship to the rear of the gun shield, and arranged to deliver or pick up shot from the working chamber.

These latter hoists work either by hydraulic power, or alternatively, by hand. Also a pair of powder hoists reaching from the bottom of the ship to a platform placed between the two guns; these work by hand only. In addition, it is provided that either shot or powder can be hoisted from below to the working chamber by hand tackle as a last resource.

Very great precautions are, therefore, as you see, taken to make

sure that the projectiles stowed below can be brought up to the gun. Nevertheless, three rounds per gun are stowed in the gunhouse, and eight rounds per gun in the working chamber.

The weight of gear for transporting shell in the shell-room and the weight of the shell hoists and their gear is about equal to 54 tons per ship, or equal to half the weight of the projectiles stowed in the shell-rooms.

In order to charge the main hoists a revolving platform is provided in the shell-room, having on each side trays for carrying a couple of projectiles. This revolving platform is first locked in one particular position to the ship, and shell are placed in the trays by overhead tackle in the shell-room. The platform is then unlocked and moved to whatever position is necessary to bring the shot trays opposite the hoist doors. It is then locked to the hoist trunk until the shot are required to be passed into the hoist cages.

To manage this heavy platform in a seaway, it has been thought necessary to revolve it by hydraulic engines. These platforms and the gear for working them have a total weight per ship of 9 tons. The alternative method of charging the hoist cages, which I myself prefer, shown on Plates XXX. and XXXI. (p. 520) and Figs. 1 and 2, Plate XXXVA. (p. 520), and which is being fitted to four Japanese ships, is by a pair of overhead circular rails, the outer one of which is fixed to the ship and the inner one to the trunk of the hoist. A small four-wheeled chariot runs upon these rails. The point of suspension of the supporting tackle carried by this chariot can be shifted so as to throw the weight entirely on the one rail or the other.

While picking up shot on the ship the load is on the wheels which run on the fixed rails. The suspension point is then shifted to throw the load on to the moving rail, so that, while the shot is being placed in the hoists, any movement of the hoists carries the projectile with it. I have already referred to the danger, which I consider exists, of small shot entering the gun ports. In these four ships this is met by providing on the top of the gun a port protector, indicated at A, Plate XXXIII. (p. 520). Alternative electrical training gear, controlled and worked by the same hand-wheel as is ordinarily used for the hydraulic training, is also being fitted for these Japanese ships.

The design for the *Formidable* and three sister ships, Plate XXXII. (p. 520), also has a working chamber below the gun turntable, and a pair of hoists in the rear of the gun. The central hoists are contained in a cylindrical casing, 6 feet 6 inches diameter, extending from the under side of the working chamber to within 2 feet of the ship's bottom.

This casing revolves with the mounting, and contains a pair of shot hoists and a pair of powder hoists.

The bottom of the casing is fitted with rails, on which a pair of bogies carrying shot trays, can run. These are arranged to be locked to the ship while being charged, and to the hoist casing while discharging into the shot cage.

The shot on arriving at the working chamber are automatically rolled out into an inclined trough leading to the gun hoists.

A new departure in this design is the loading of the guns at an elevation of only $4\frac{1}{2}°$. I believe there is an impression that time can be saved if the guns can be loaded at any angle without coming to a fixed position. If, however, the gun has to be washed out after each round, it would have to be placed at about 4° or 5° of elevation, to allow the water to run out of the chamber. This, and the provision of something to catch the water, seems to make it desirable to place the gun on a stop at this position. On the comparatively rare occasions when more elevation is required, the stop can be easily removed.

In the design of mounting shown on Plate XXXIII. (p. 520) for the Japanese ship *Mikasa*, the outer casing of the hoists is built watertight at the middle, lower, and platform decks, each of which will therefore be strengthened and bound together. The interior and bottom portions of the hoist are practically the same, and revolve within the fixed casing. This design of hoist is also adopted for the Italian ships *Regina Margherita* and *B. Brin.*

On Plate XXXII. (p. 520) is shown a chain rammer. About the use of these chain rammers there is some difference of opinion among authorities. In a fixed loading arrangement it is quite possible that a chain rammer might be advantageously used to save room by reducing the lengths of the oval barbette; but, as now applied to all-round loading arrangements, its use appears to me to be doubtful. In the hydraulic rammer we have a machine placed in a line with the work to be done, and making a stroke in a straight line, so that nothing more direct-acting could be devised for the purpose; and I confess, under the existing circumstances, I fail to see the advantage of a mechanism which first converts rectilinear motion into circular motion, and then converts the circular back again to rectilinear. Moreover, the hydraulic rammer shown on Plate XXXIII. (p. 520), in a similar position to that occupied by the chain rammer, is made up of far fewer pieces, and weighs only one-fourth as much as the chain rammer of similar power.

I have gone rather fully into the central hoist question, because, when the all-round loading of guns is to be arranged for, the difficulty at once presents itself of how to get the projectiles and charges transferred from the ship to the gun turntable, not only in every position the latter might take up in relation to the ship, but also while the gun turntable is moving or is liable to be moved at any moment.

You will notice that in the *Re Umberto* this difficulty is met by using a turntable top to the central hoist, and sliding the projectiles radially outwards into the gun hoists. In the *Canopus*, by the employment of overhead travelling cranes placed above the central hoists; in the *Albion*, by surrounding the bottom of the ammunition trunk by a revolving platform running on rails on the ship's bottom, and capable of being locked either to the ship or the hoist trunk; in the *Shikishima*, by using a double overhead rail, half of which moves with the hoist and the other half a fixture to the ship; and in the *Formidable*, by having two shot carriages running on rails carried at the bottom of the trunk of the hoist.

There are objections to each of these systems, and perhaps they all make too much of what is, after all, a very simple matter. If the hoist cage carrying the projectile can be made to vary its position according to the training of the gun during its ascent from the shell-room all difficulty will be overcome. I wish, therefore, to draw your attention to the design in Plate XXXIV. (p. 520), due to my friend Mr Murray, which accomplishes, I think, exceedingly satisfactorily this end.

In this design there is a small fixed central trunk, 2 feet 9 inches outside diameter, which forms a strong pillar guide for a pair of ammunition cages. The back of each ammunition cage is curved to fit partially round this pillar. There is also an outer trunk of about 6 feet 6 inches diameter built to the ship. This outer casing is smooth inside, and the ammunition cages are prevented from falling away from the central pillar because their outer edges are in contact with the outer casing. It will thus be seen, as the cages move up and down, they could be slewed round the pillar or travel up it in a spiral line.

In order to make the cages follow the desired path, the central pillar is clasped at convenient intervals by several rings sunk in the thickness of its plate, so as not to prevent a free passage. Each of these rings carries an arm on either side, and a pair of ropes kept taut by springs are stretched from top to bottom and pass through

an eye at the end of each arm. The stretched ropes are secured at the bottom to the ship, and at the top to the under side of the gun turntable. As the turntable is trained to right or left, the ropes take up a spiral position, and, by means of the arms upon the rings round the pillar, guides for the cage, which are also carried on the arms, are likewise compelled to take a spiral form.

With this arrangement a most satisfactory method of charging the cages in the shell-room can be employed. This will be seen on Plate XXXV. (p. 520).

Troughs are provided in line with the position to which the cages always descend. Overhead hydraulic and hand-worked runners command these troughs and shell bins.

Hydraulic rammers are placed in line with the troughs for pushing the shot which has been set in the troughs into the cage. On the other side of the trunk the magazine handing-rooms are arranged; so that, while the shot are being placed in the cage on one side, the powder can be placed from the other side.

With this arrangement any shot from the bins can be picked up and put into either cage, and the whole arrangement is simpler and more complete than has yet been fitted on any ship in this respect.

In the working chamber the cages always arrive by the side of the trough in line with the gun hoists, into which the shot is automatically rolled. A hand or hydraulic rammer can be used to slide the shot down into the gun hoists, and the powder is transferred by hand in quarter-charges.

This is, of course, assuming that the current opinion is in favour of a transference of the ammunition in the working chamber.

In Plates XXXVI. and XXXVII. (p. 520), is shown a design in which the central hoist is not stopped at the working chamber, but is carried on to the rear of the guns. There are, I believe, those who fear that this arrangement would give too direct a path for fire to the magazine in case of any accident at the gun. The difference between this and any other system is so very slight that, with proper precautionary measures, I do not think there need be any fear. It seems to me that, if it is decided that the shell ought to be at the bottom of the ship, the most perfect arrangement is that in which any shot can be conveyed from any shot bin to either gun in whatever position the gun may be, entirely by mechanical means, and without having to handle it.

In concluding this part of my subject, I venture to draw

attention to one point. In an earlier part of my paper I have alluded to the rough and ready appliances with which the navy of the past achieved such great things, and I myself have heard distinguished naval officers urge that mechanical contrivances which could not at sea be repaired by the crew were out of place on board men-of-war.

All this is now changed. A battleship carries well on to a hundred machines of the most varied, and some of the most complicated character. I have elsewhere expressed my admiration of the ability and zeal with which naval officers of the present day have mastered, and the skill with which they use their varied machinery, but I think there is some tendency to push automatic arrangements too far. The blue-jacket will lose much, if he is degraded into a mere machine, and, in regard to the heavy mountings I have been describing, our aim should be to obtain efficiency with as great simplicity and as few complications as possible.

The number of explosives which have been used or proposed as bursting charges for shell, is very large, but in this short sketch I shall confine my attention to three—gunpowder, guncotton, and melinite, including under this latter head the form known to our service as lyddite. Mr Vavasseur and the writer were placed in a position to communicate to the authorities of this country full details concerning this last explosive, and the whole of the first experiments with it were made either by, or under the superintendence of, my firm. Guncotton and lyddite are not only capable of detonation, but also possess a potential energy very much higher than that of gunpowder.

Fired against unarmoured structures, shell charged with gunpowder do not generally explode until they are some short distance within the side of the vessel, but with guncotton and lyddite two alternatives have to be considered. The shell may either be fired with a fuse and detonator so arranged that the shell will burst immediately on impact, or it may be so arranged as to give rise to a slight delay, or hang fire.

In the first alternative the shell will burst instantaneously on impact, a result impossible to obtain with gunpowder; and in such cases a hole of very large dimensions, and impossible to plug, will be made in the side of the ship, while the innumerable small fragments to which the shell is reduced sweep the deck in the wake of the shell.

In the second alternative the shell will probably burst inside,

making only a small hole in the side of the vessel; but the full effect of the explosion, and the destruction to the crew from the fragments of the shell would undoubtedly be serious, and the cone of dispersion of the fragments much larger, from the explosion taking place inside the vessel.

Shell charged with gunpowder fired against unarmoured structures possess, however, one great advantage. The shell will probably burst from 2 to 4 feet inside the vessel, and, although the dispersion of the fragments is not nearly so great as with high explosives, the large fragments into which the shell parts, are capable of doing much more serious damage to any portion of the ship's structure with which they may come in contact.

If fired at armoured structures, the results will greatly depend upon the thickness and resistance of the plates, and on the size and energy of the attacking projectile.

Generally, it may be stated that armour is a most effective protection against high explosives, the shell in the large majority of circumstances bursting comparatively harmlessly against the armour. Even if unfused, but with detonator, and possessing sufficient energy to penetrate the plate, the shell will burst in passing through, but the dispersion of the fragments is not very great.

If fired without fuse or detonator, wet guncotton will not explode, but melinite or lyddite probably will, the result to a great extent depending on the thickness of the armour.

From the numerous experiments we have made, either ourselves in this country or elsewhere, I draw the following conclusions:—

(1) To attack unarmoured structures, I have no doubt that shell charged with high explosives are a most formidable weapon. The large quantity of explosive that can be carried, and the power of immediately detonating the shell, permit the vessel to be attacked, either by making large holes at or near the water-line, or if the shell should burst inboard, the effect of the explosion and the destruction to everything in the wake of the shell would be very serious.

(2) But with high explosives the shells are reduced to very small fragments, and even very thin steel plates resist penetration. Hence the importance of traverses; and, supposing a first-class cruiser to engage two smaller cruisers firing high explosives, one on each broadside, a longitudinal traverse of very moderate thickness would be a protection, the importance of which could hardly be overrated.

(3) Having regard to the size of the holes made by high explosives in unarmoured structures, I regard it of great importance that, where-

ever possible, the water-line should be protected from stem to stern with a belt of armour, and that side armour should be provided where guns are carried on the main deck. On the upper deck effective shields, and as thick as can be conveniently carried, should be attached to the mountings.

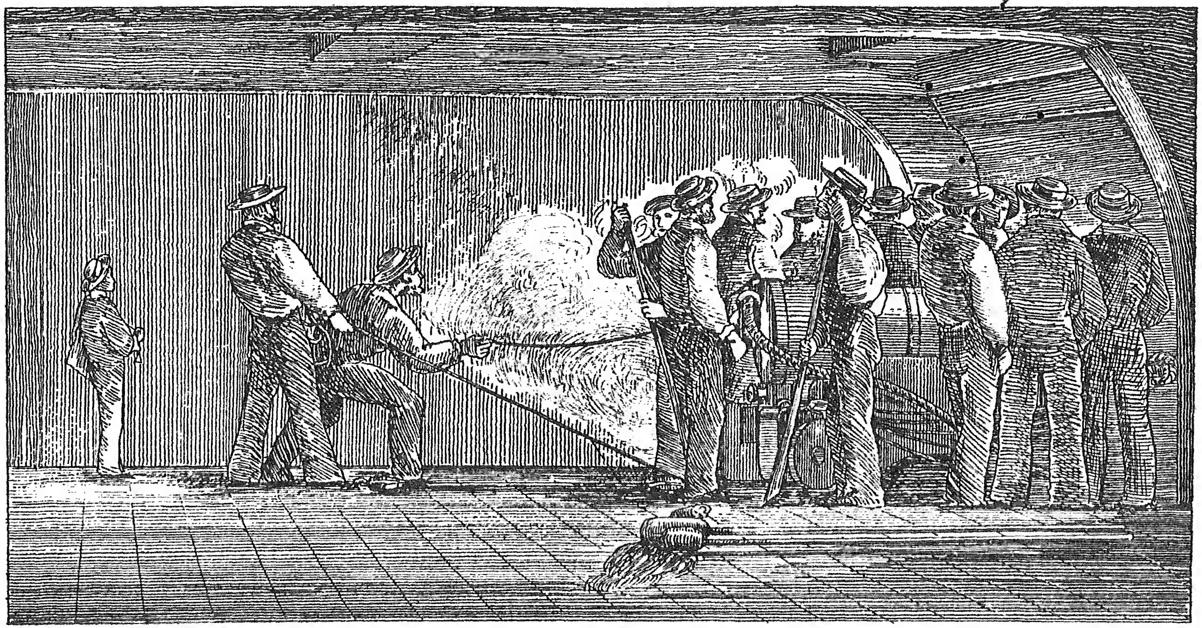
(4) Where an attack is made against thin armour, shell charged with gunpowder are more effective than high explosive shell, as, dependent on circumstances, the former can be got to pass through thin armour and burst inside. I doubt if shell charged with any explosives can be got to pass through thick armour without bursting.

(5) There is one serious objection to certain high explosives, as bursting charges, which is not shared by wet guncotton, and that is, the liability to detonate if struck by another projectile, or even by a large fragment. Wet guncotton is quite safe in this respect, and yet, if fired, for example, by a fulminate, it detonates even more rapidly than in the dry state. This property has led certain governments to adopt it as the high explosives for use on board ship.

In concluding this paper I desire to defend our Elswick practice, which I have sometimes heard attacked, of mounting as many guns on the broadside as can be conveniently carried. Personally, I share strongly the opinion which a distinguished admiral once expressed to me: that, supposing a fight between two cruisers equally ably commanded, the victory would remain with the ship that got in first her second broadside, and the victory would be more assured if her broadside were the more powerful. It must also be remembered that with our modern weapons, allowance must be made for a gun, or two, being disabled without altogether crippling the broadside. For these reasons I prefer to carry as many guns as possible, even if the number of rounds carried per gun be reduced.

I feel that I ought perhaps to apologise for the length of this paper; I may, however, make the excuse which I have before heard, that I have been so much pressed with other work, I had not time to make it short. I must, however, express my obligations to my friends and fellow-workers, Mr Murray and Mr Brankston, who, with this paper, as in many other ways, have given me most valuable assistance.

PLATE I.

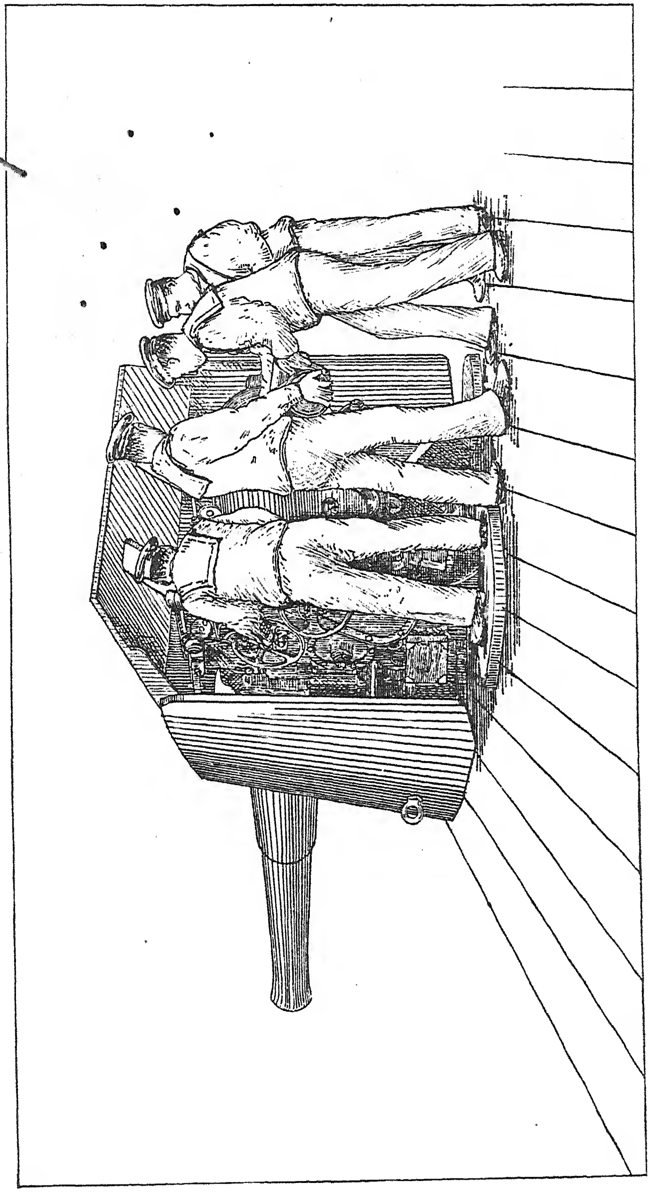


A GUN'S CREW OF H. M. SHIP "EXCELLENT" (1860)

READY!

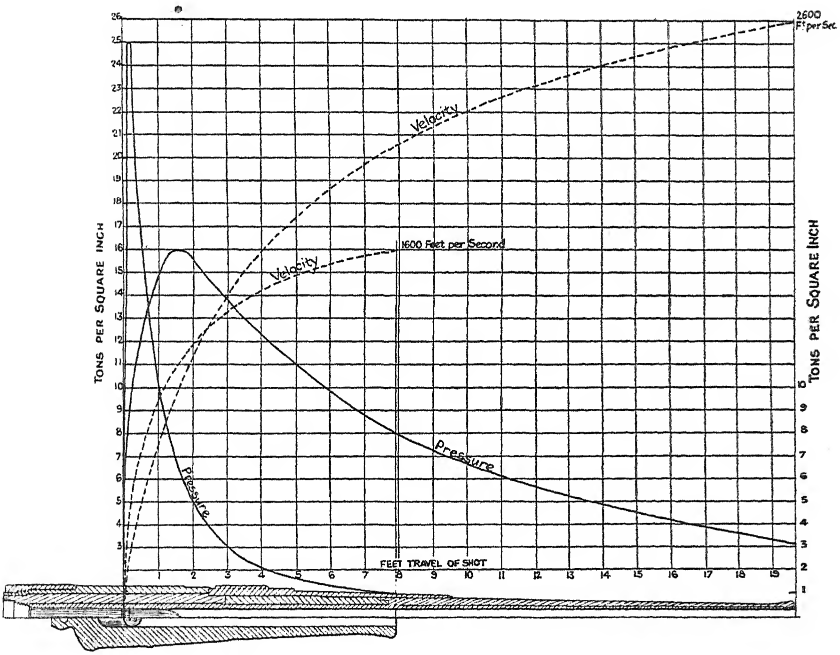
[*Between pp.* 520-21.

PLATE II.



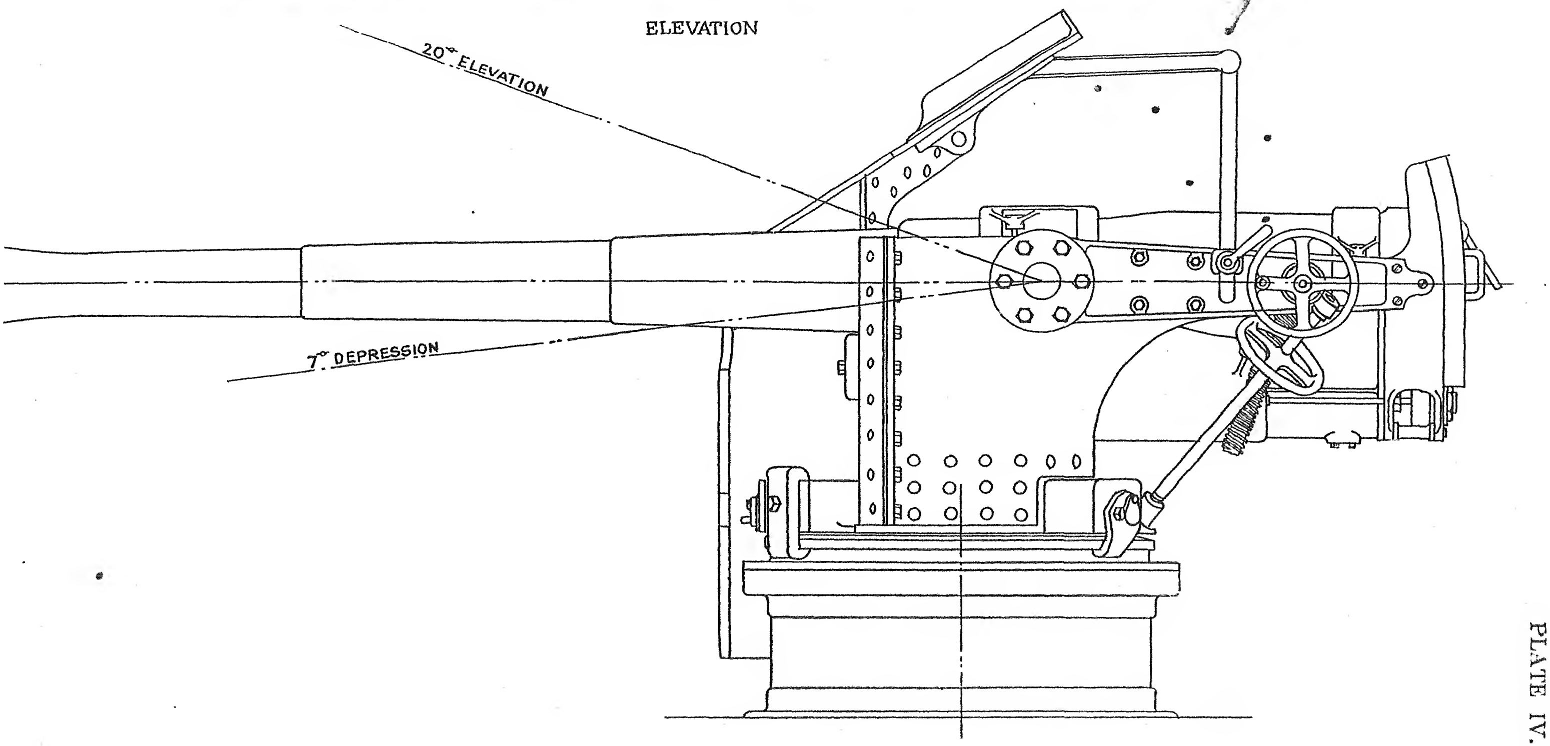
6 INCH Q.F. GUN (1899)

COMPARISON BETWEEN A 32 Pr. OLD GUN AND A 6 INCH NEW GUN



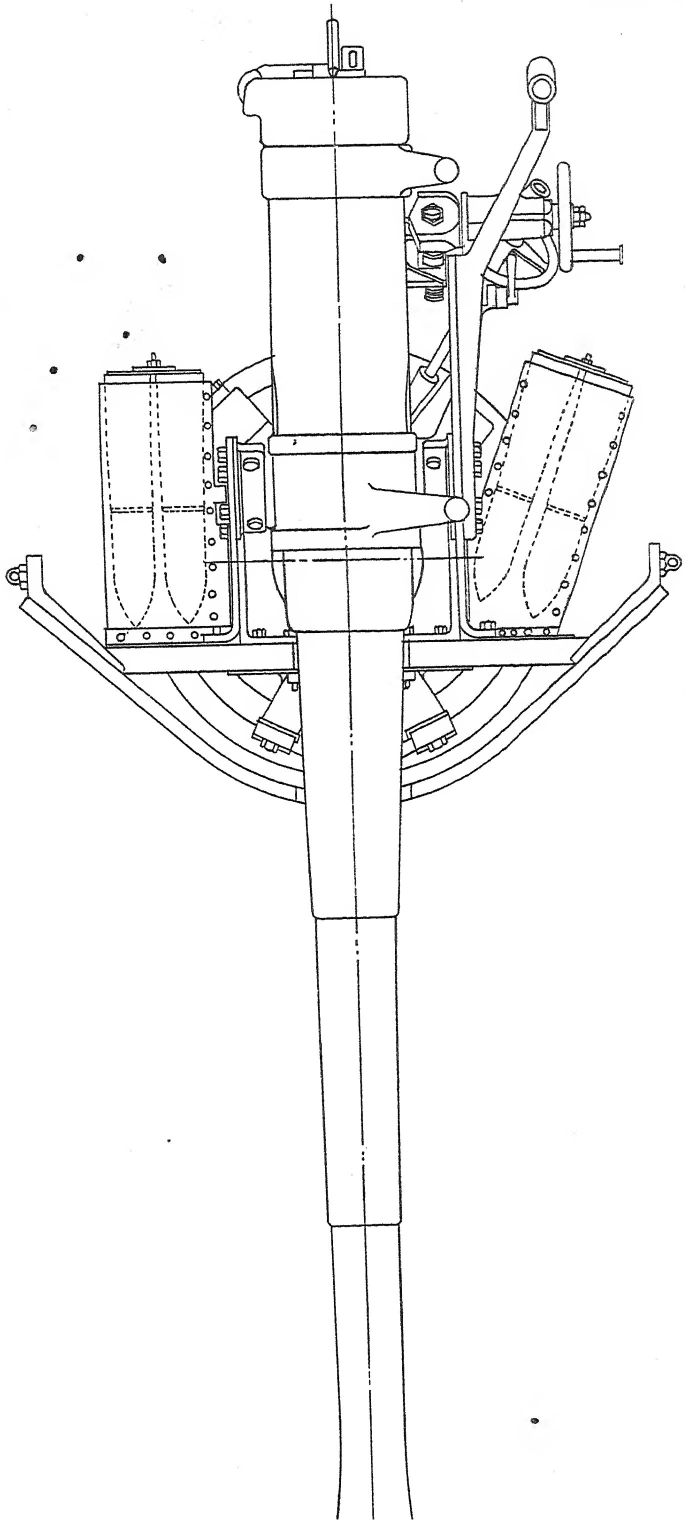
4·724 INCH 36 PR Q.F. GUN ON CENTRE PIVOT RECOIL MOUNTING.

ELEVATION



4·724 INCH 36 PR. Q.F. GUN ON CENTRE PIVOT RECOIL MOUNTING.

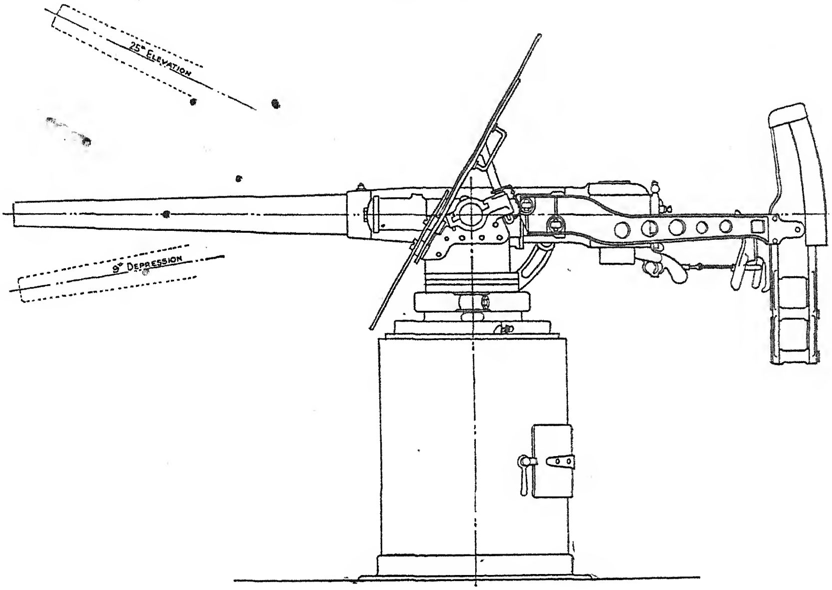
PLAN



47 M/M 3 PR. QUICK FIRING GUN ON ELSWICK PEDESTAL RECOIL MOUNTING.

ELEVATION

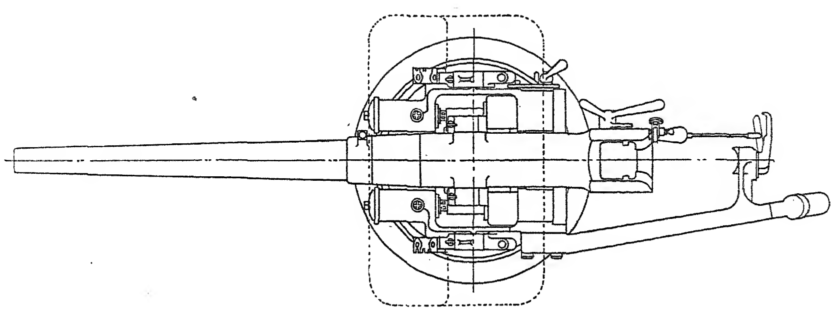
40 Calibre Gun



47 M/M 3 PR. QUICK FIRING GUN ON ELSWICK PEDESTAL RECOIL MOUNTING

PLAN

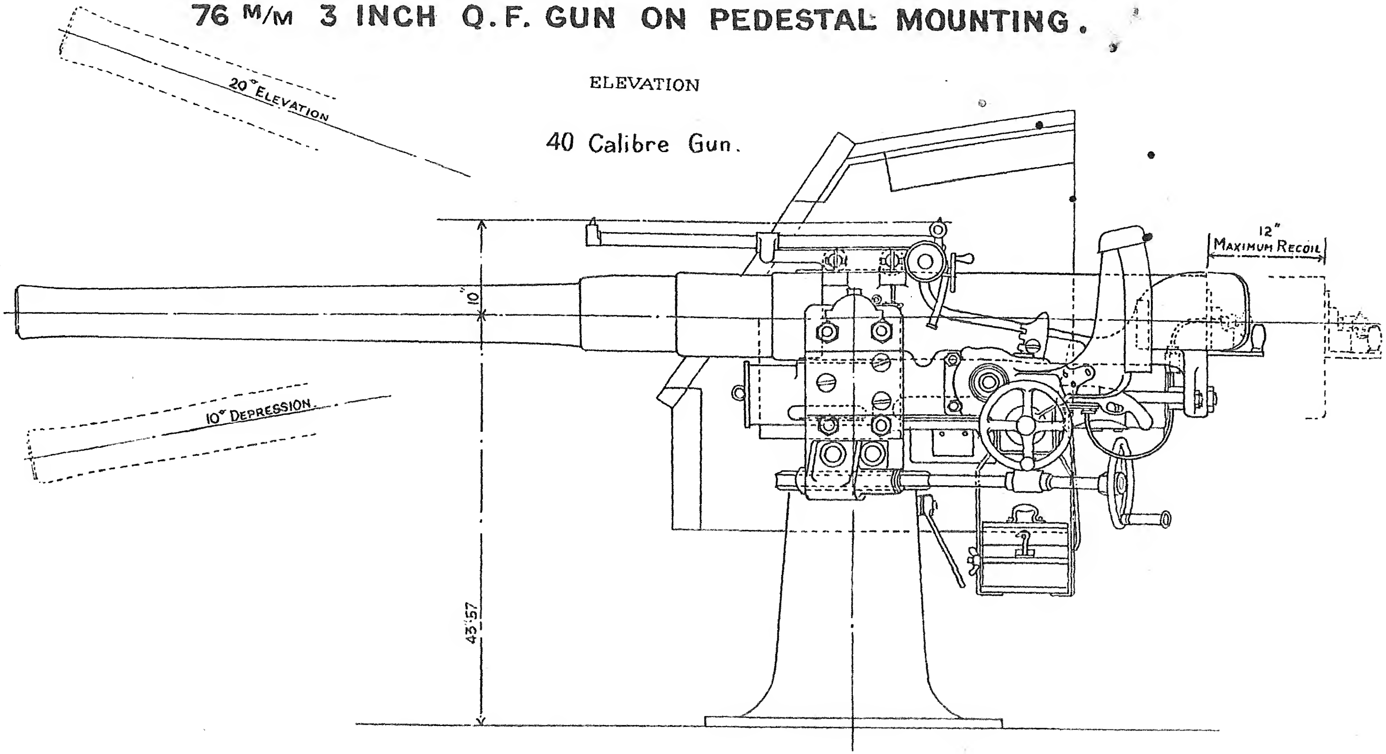
40 Calibre Gun.



76 M/M 3 INCH Q.F. GUN ON PEDESTAL MOUNTING.

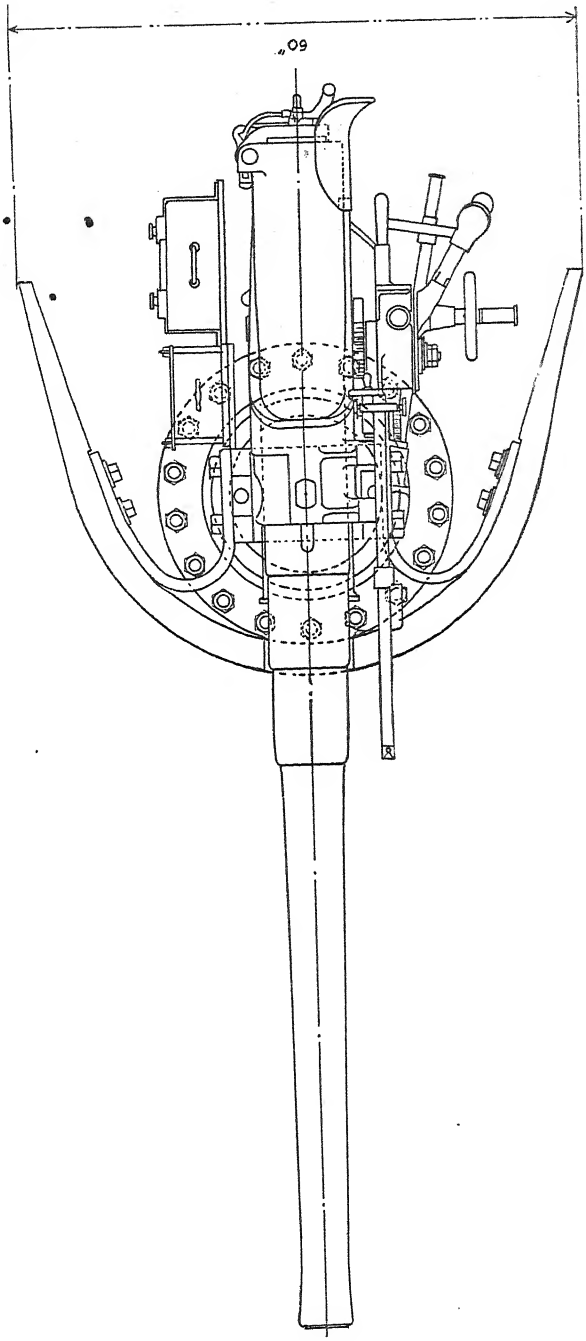
ELEVATION

40 Calibre Gun.



76 M/M 3 INCH Q.F. GUN ON PEDESTAL MOUNTING.

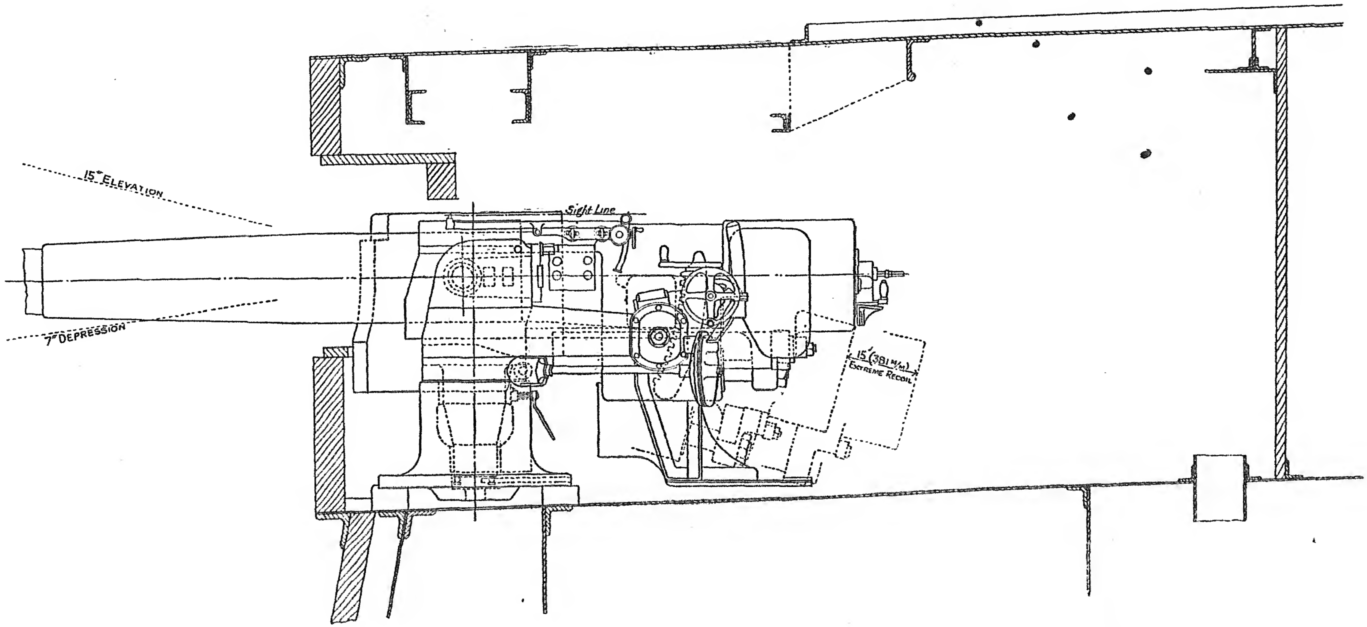
PLAN



6 INCH 152 M/M Q.F. GUN ON BETWEEN DECK MOUNTING IN CASEMATE

45 Calibre Gun.

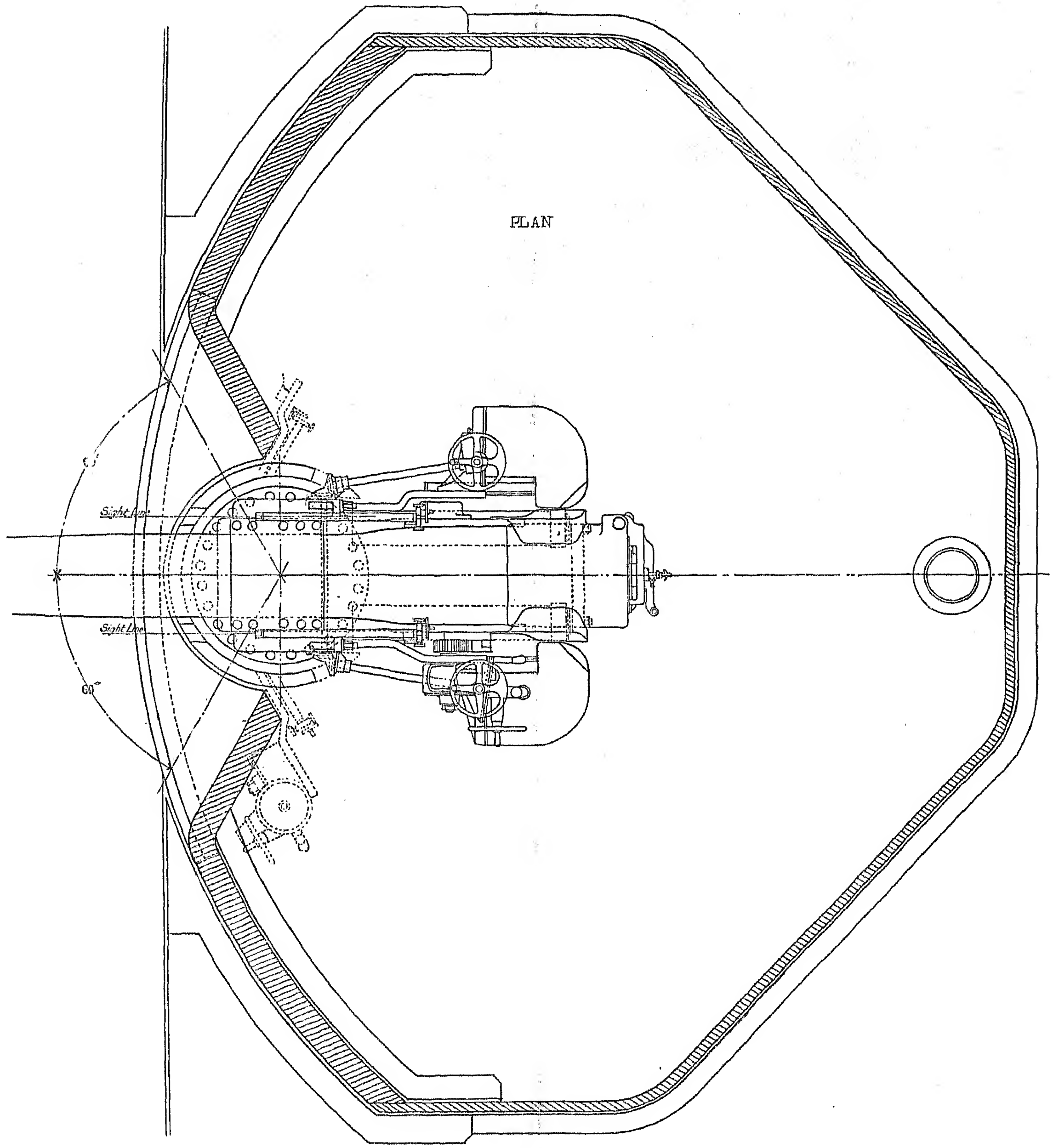
ELEVATION.



[Between pp. 520-21.

6 INCH 152 M/M Q.F. GUN ON BETWEEN DECK MOUNTING IN CASEMATE

45 Calibre Gun



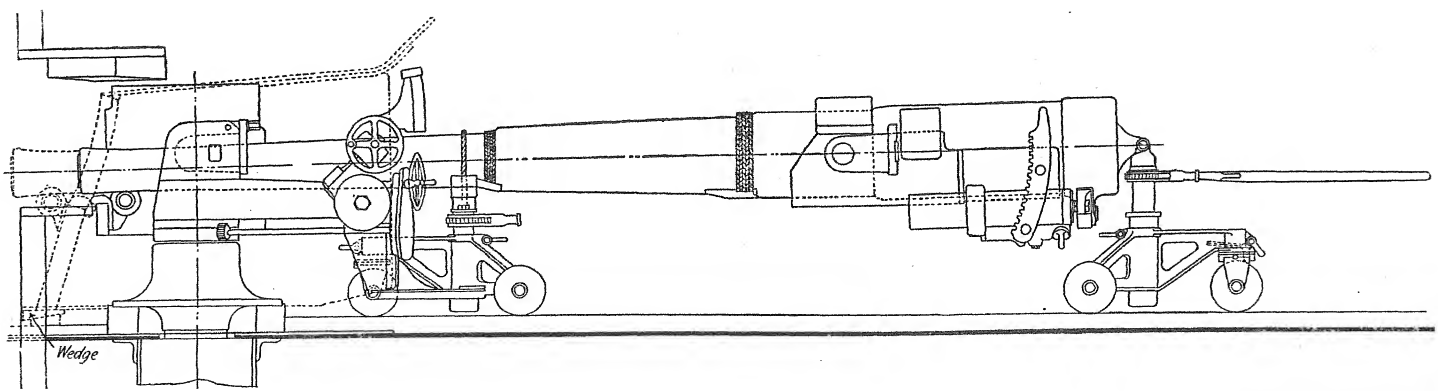
[*Inset between* Pl. X. and XII., pp. 520-21.

DISMOUNTING GEAR FOR 6 INCH 152 M/M Q. F. GUNS ON PEDESTAL MOUNTINGS

CASEMATE AND UPPER-DECK GEAR.

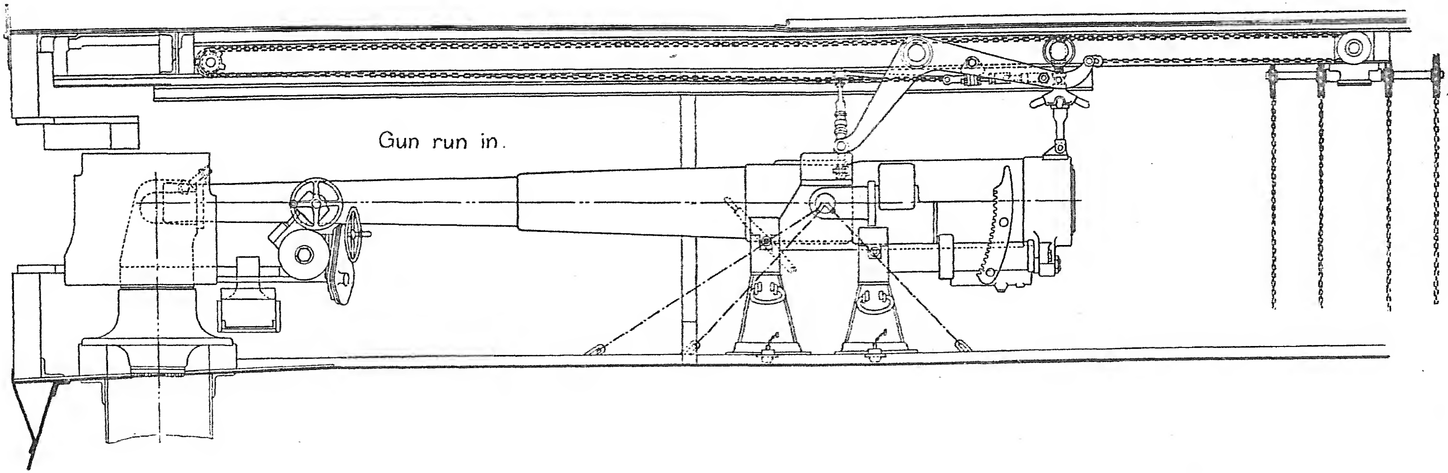
Shield on Upper-Deck Mtg. shewn dotted.

Gun run in.



DISMOUNTING GEAR FOR 6 INCH 152 M/M Q. F. GUNS ON PEDESTAL MOUNTINGS

BETWEEN DECK

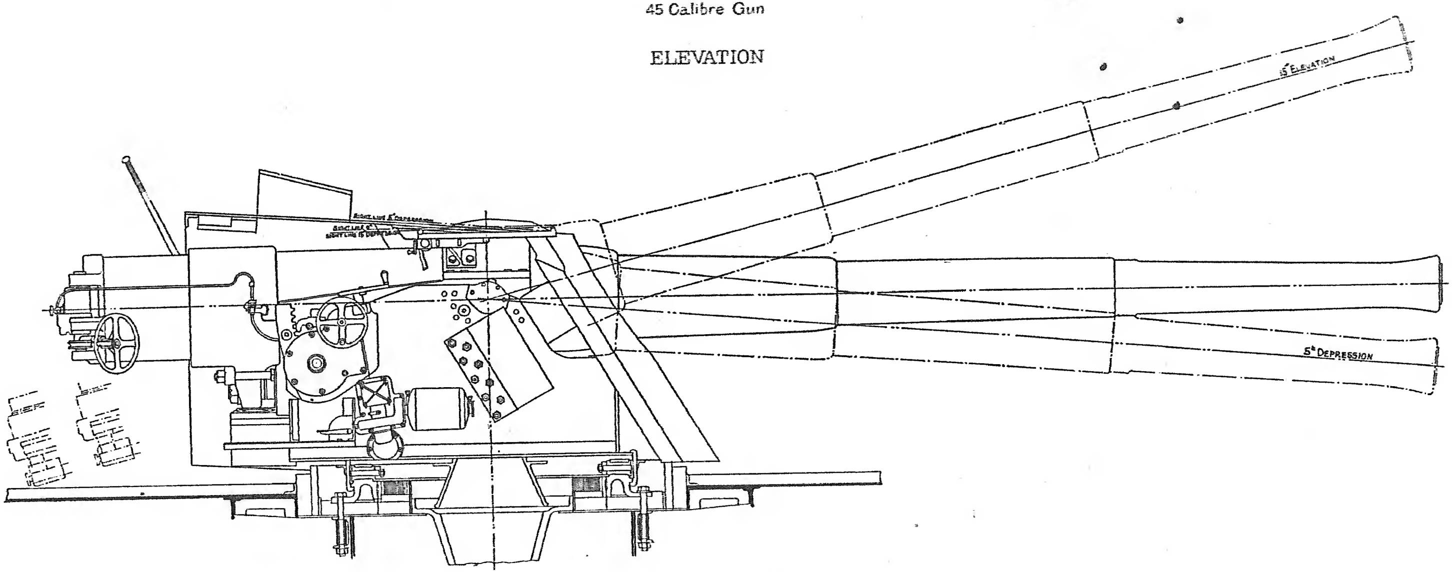


H.I.J.M.S. "TAKASAGO."

8 INCH 203 M/M Q . F. GUN ON AUTOMATIC CENTRE PIVOT MOUNTING

45 Calibre Gun

ELEVATION

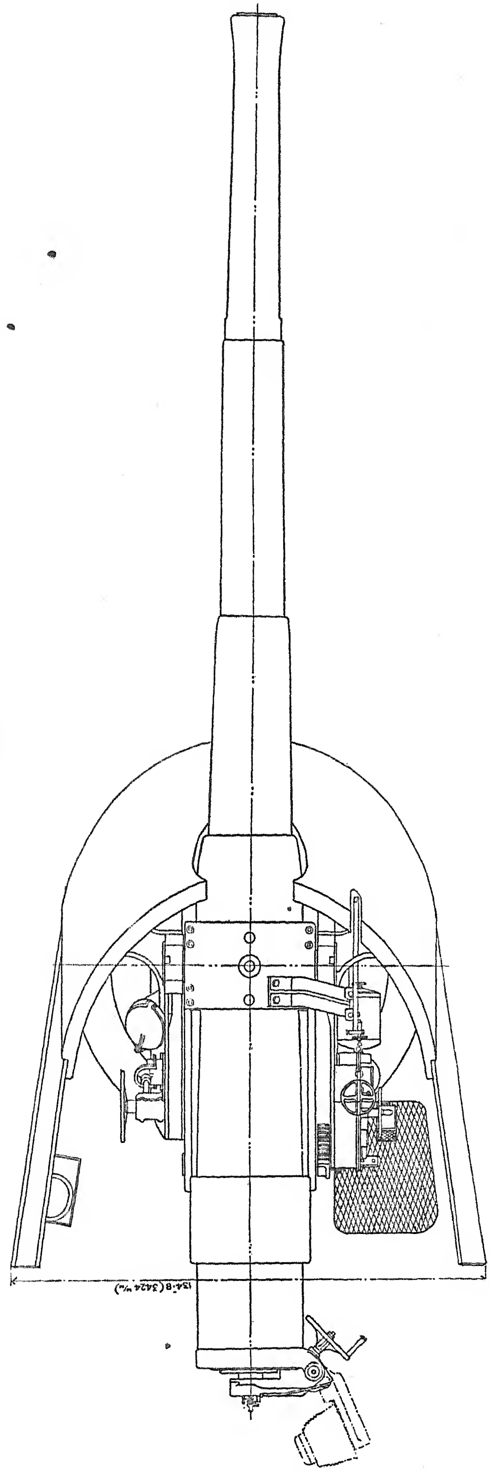


H.I.J.M.S. "TAKASAGO"

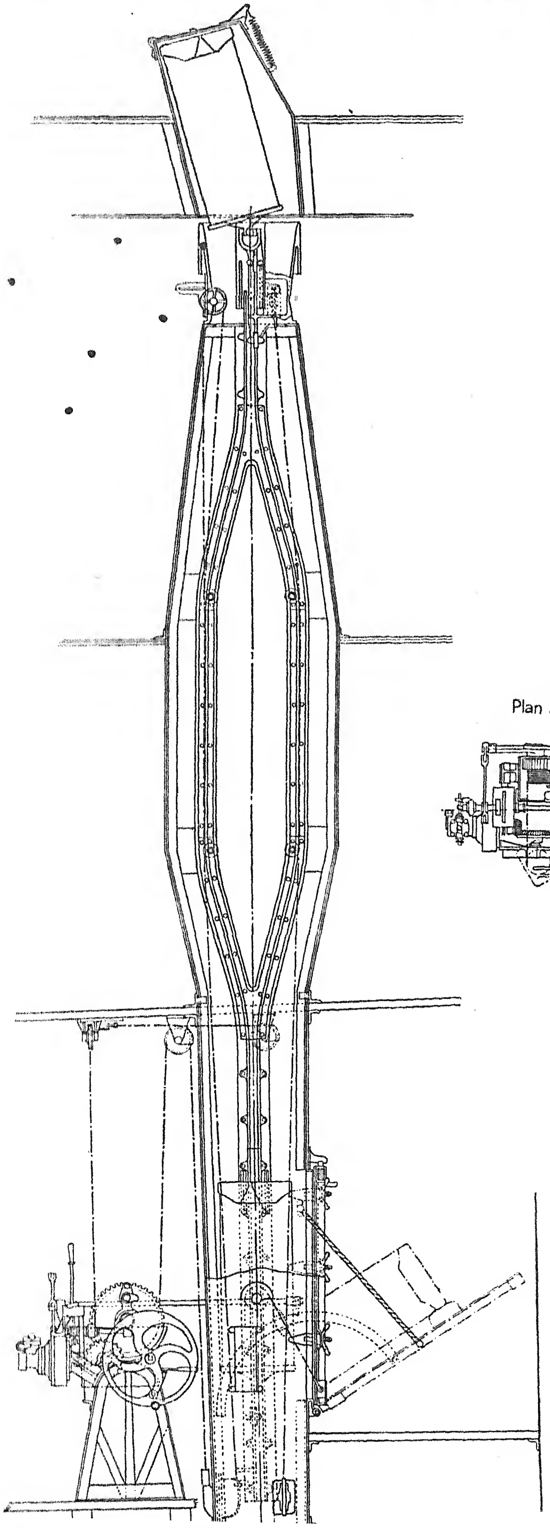
8 INCH 203 M/M Q.F. GUN ON AUTOMATIC CENTRE PIVOT MOUNTING

45 Calibre Gun.

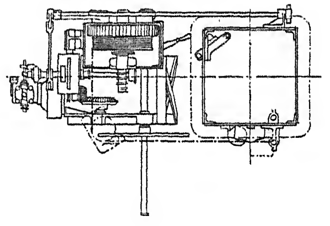
PLAN



ARRANGEMENT OF 8 INCH AXIAL POWDER HOIST.

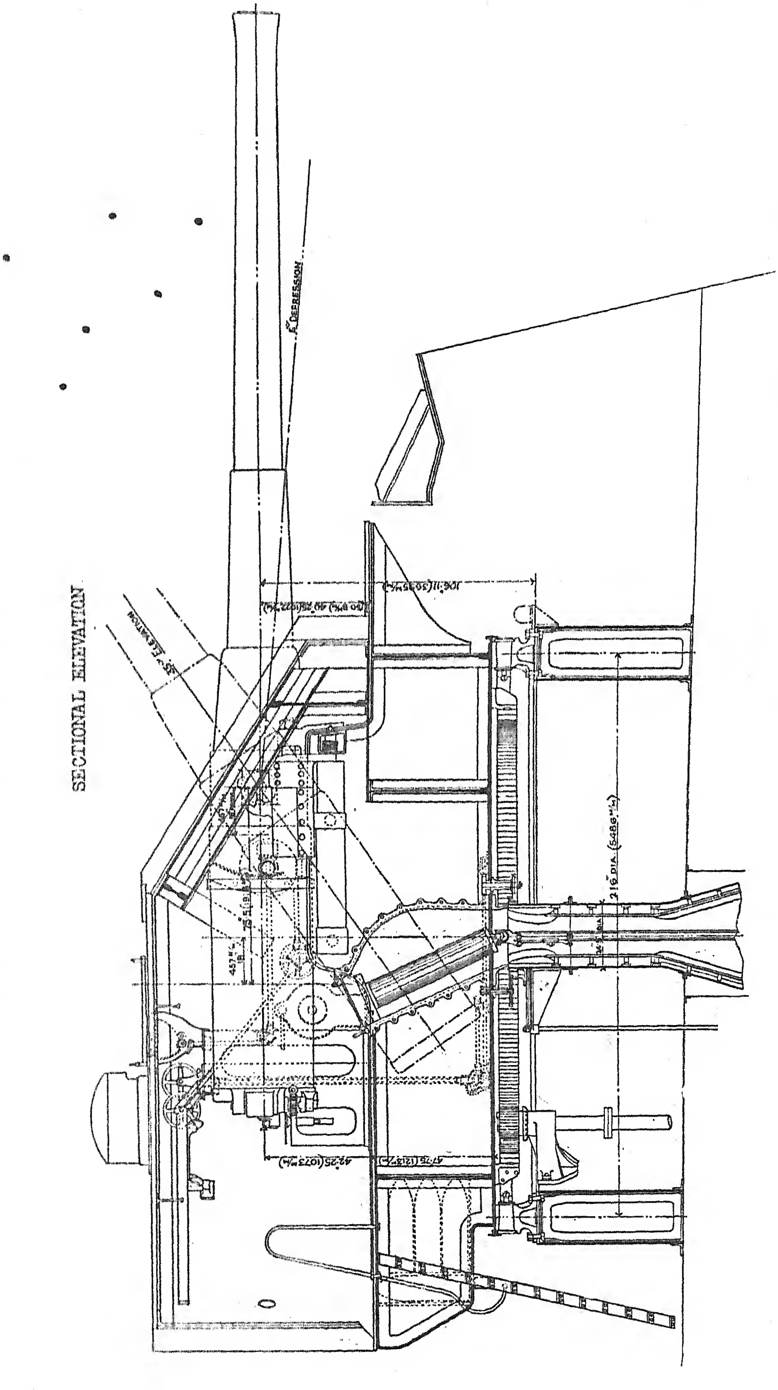


Plan shewing lead of ropes



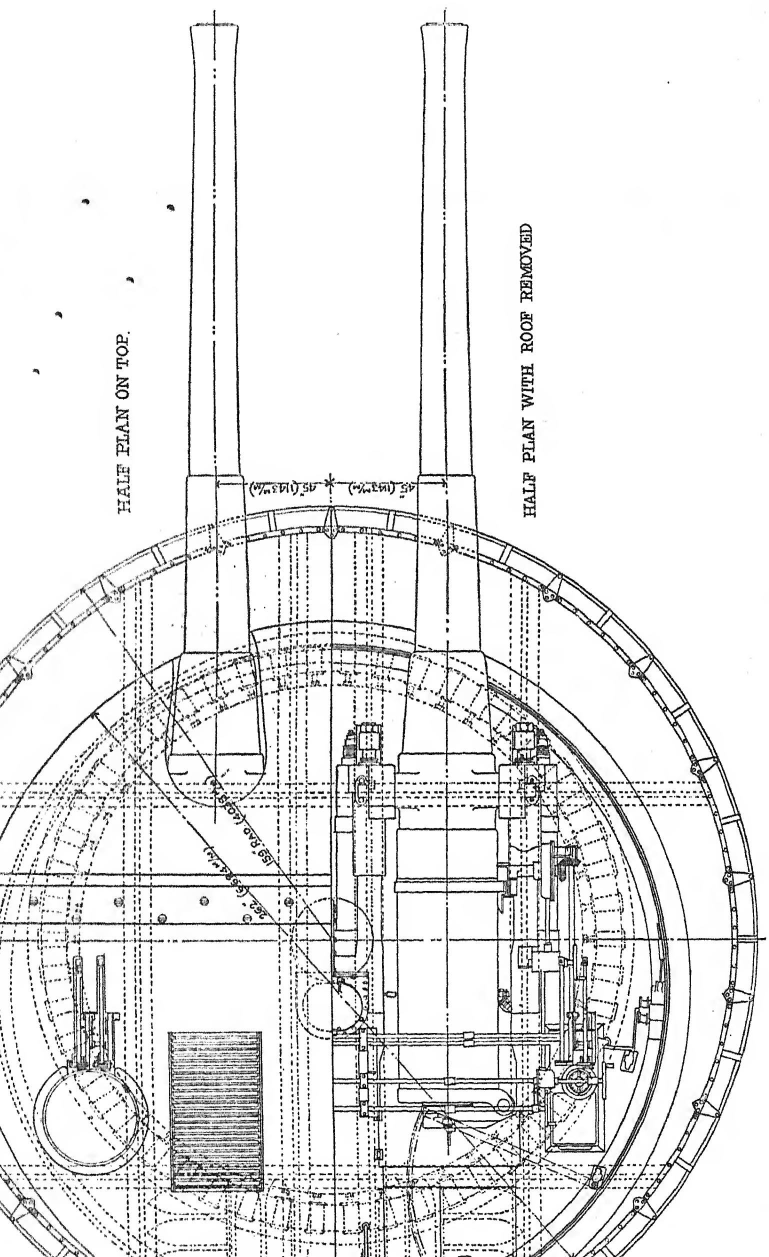
H.I.M.S.S "DANDOLO", "AMMIRAGLIO ST. BON", "EMANUELE FILIBERTO".

GENERAL ARRANGEMENT OF TWIN MOUNTING FOR 254 M/M B.L. GUNS.



H.I.M.Ss "DANDOLO," "AMMIRAGLIO St BON," "EMANUELE FILIBERTO."

GENERAL ARRANGEMENT OF TWIN MOUNTING FOR 254 M/M B.L.GUNS.

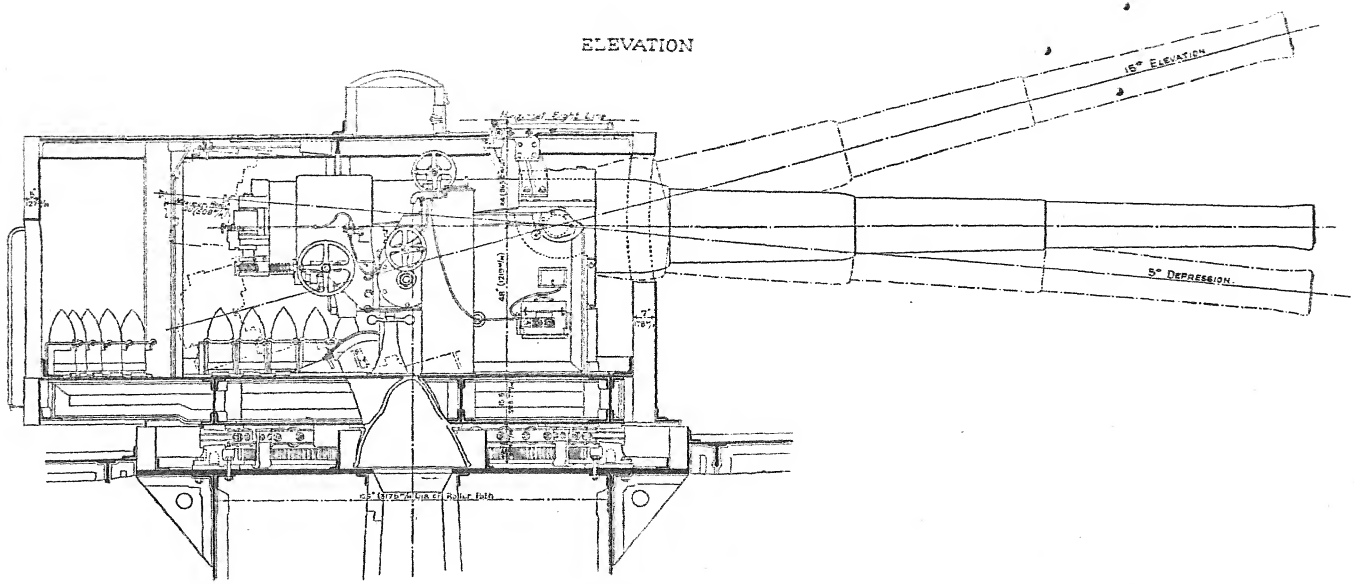


CHILIAN CRUISER "GENERAL O'HIGGINS".

8 INCH 203 M/M Q. F. GUN IN ARMOURED GUN HOUSE.

40 Calibre Gun.

ELEVATION



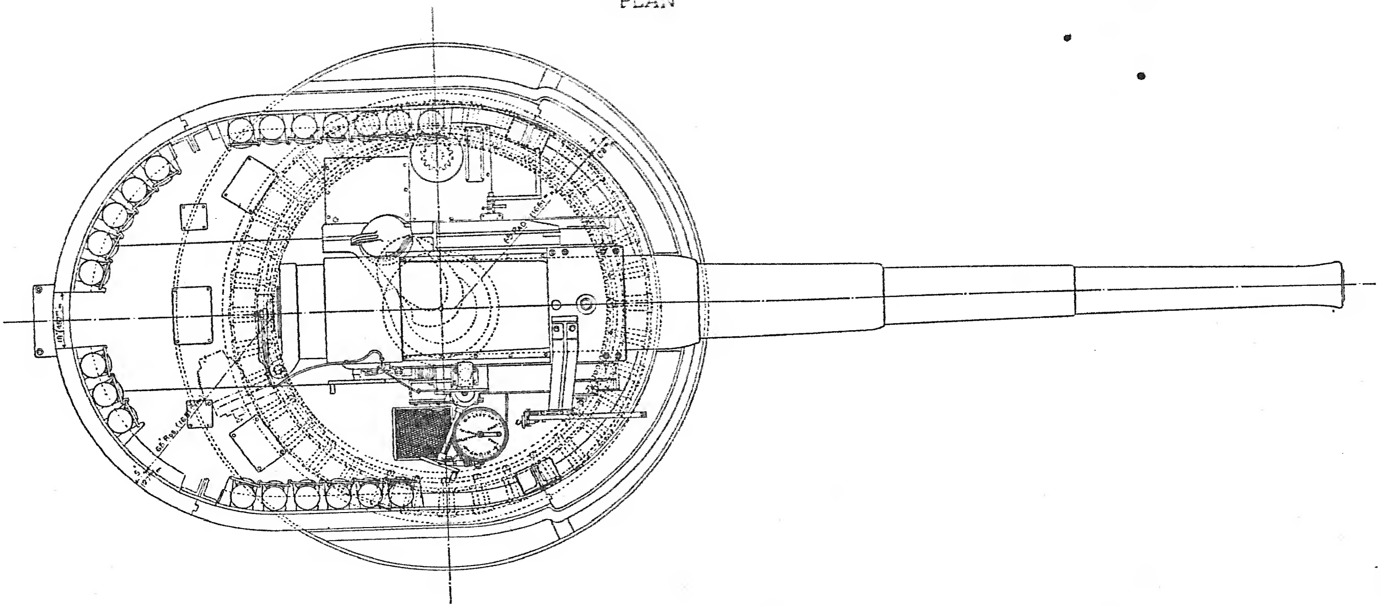
[Between pp. 520-21.

Chilian Cruiser "General O'Higgins."

8 INCH 203 M/M Q. F. GUN IN ARMOURED GUN HOUSE.

40 Calibre Gun

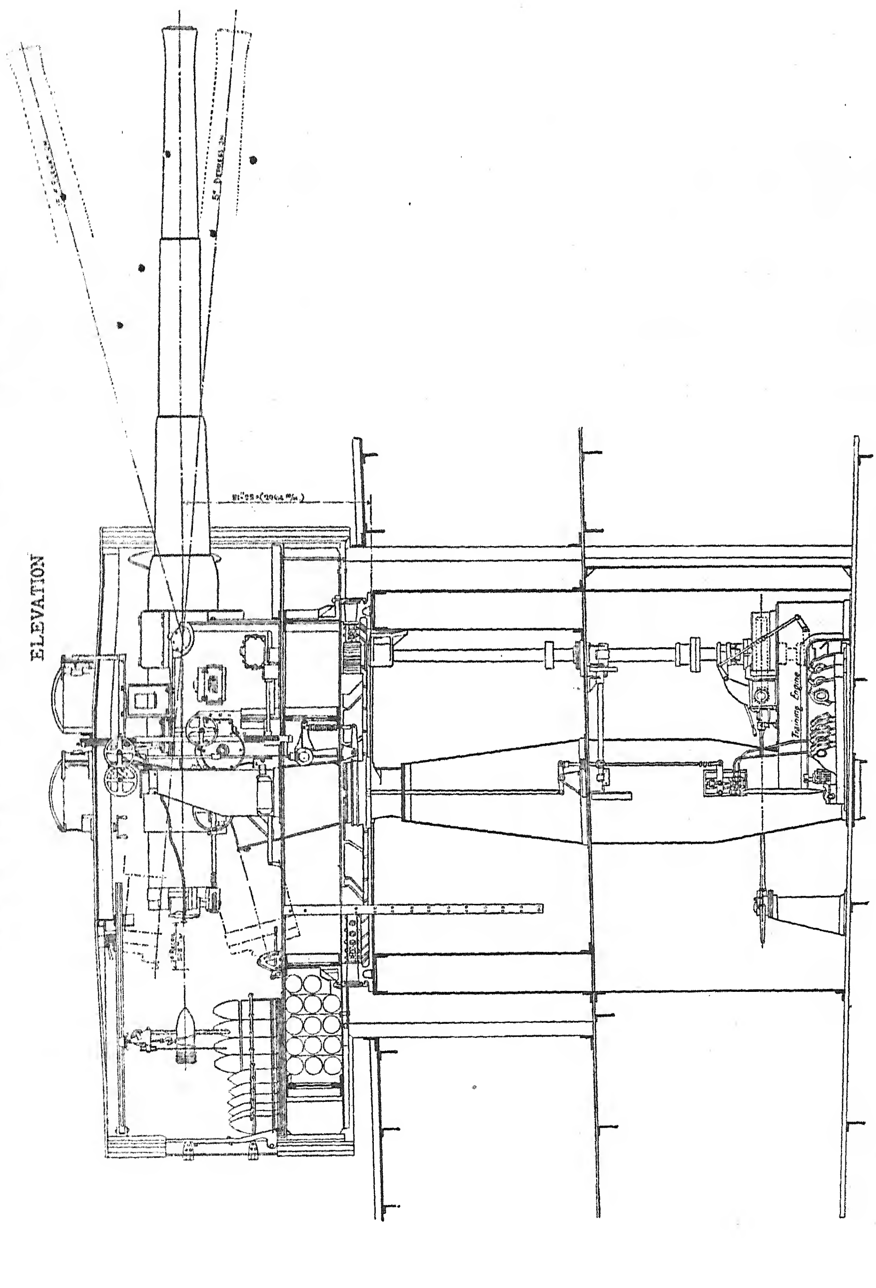
PLAN



H.I.J.M.S.S "ASAMA" & "TOKIWA".

TWIN MOUNTING IN ARMOURED GUN HOUSE FOR 8 INCH 203 M/M Q.F. GUNS

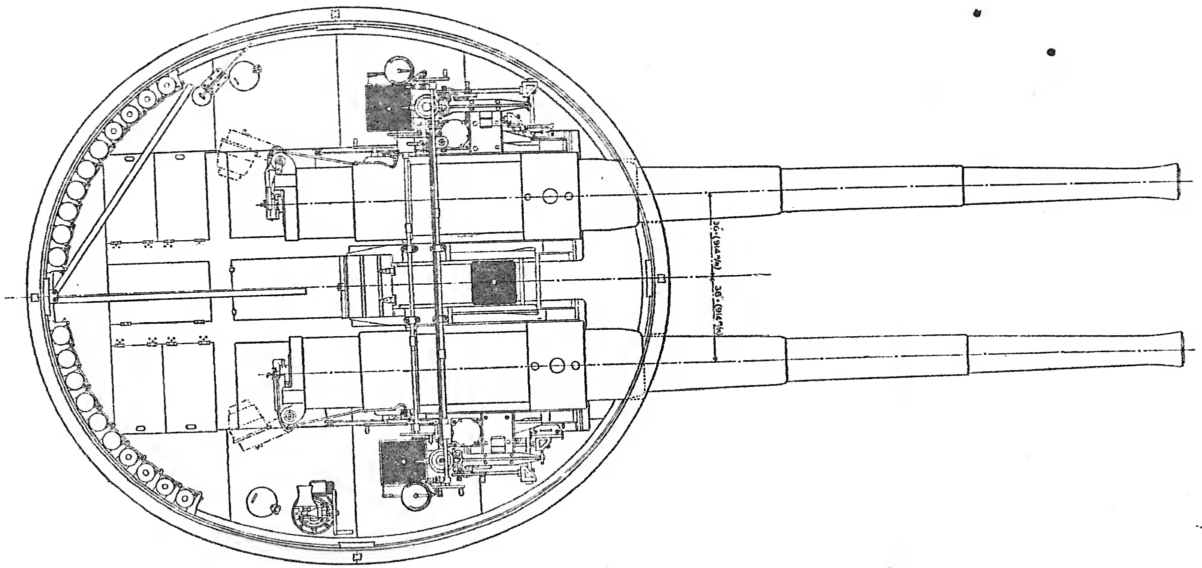
ELEVATION



H.I.J.M.S^{s} "ASAMA" & "TOKIWA."

TWIN MOUNTING IN ARMOURED GUN HOUSE FOR 8 INCH 203 M/M Q.F. GUNS.

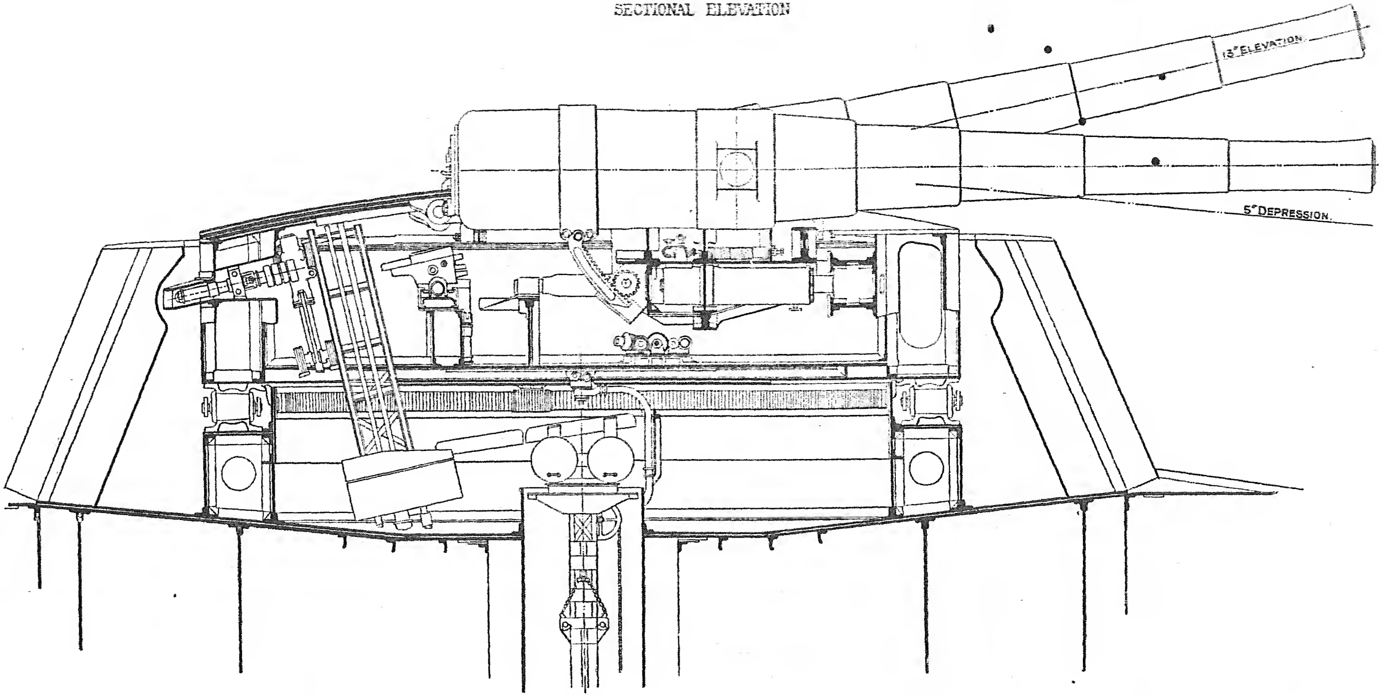
PLAN WITH ROOF OF HOUSE REMOVED



H.I.M.S "Re Umberto."

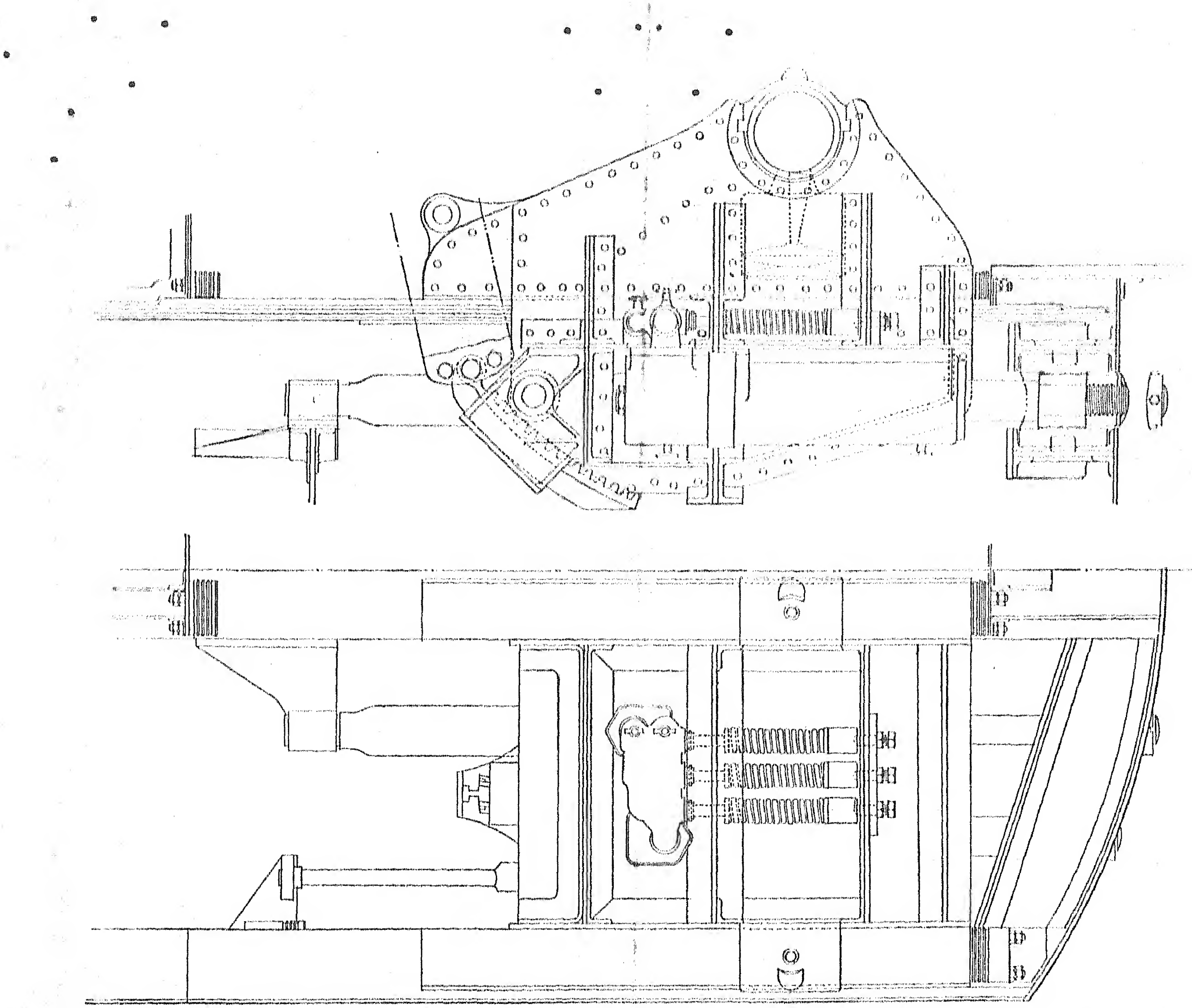
GENERAL ARRANGEMENT OF TURRET AND MOUNTING FOR A PAIR OF 13·5 INCH 68 TON B.L. GUNS

SECTIONAL ELEVATION



H.I.M.S. "RE UMBERTO".

ARRANGEMENT OF GUN CARRIAGE AND SLIDES.

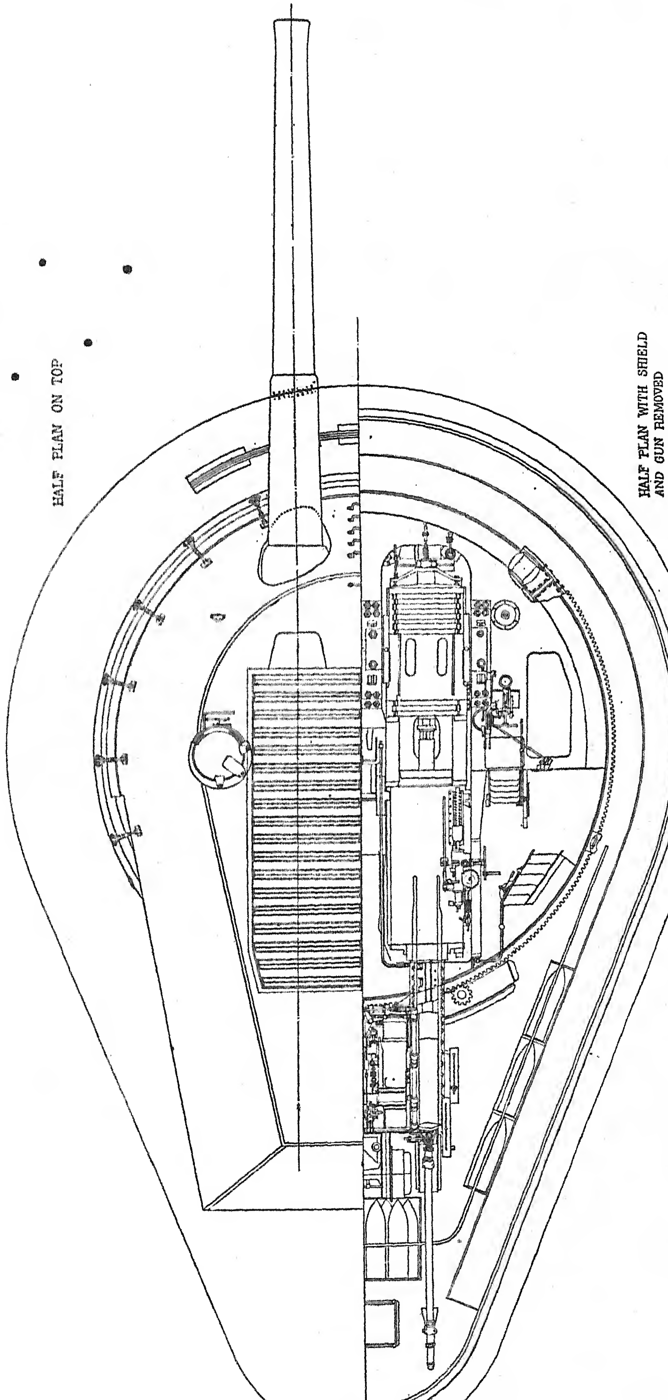


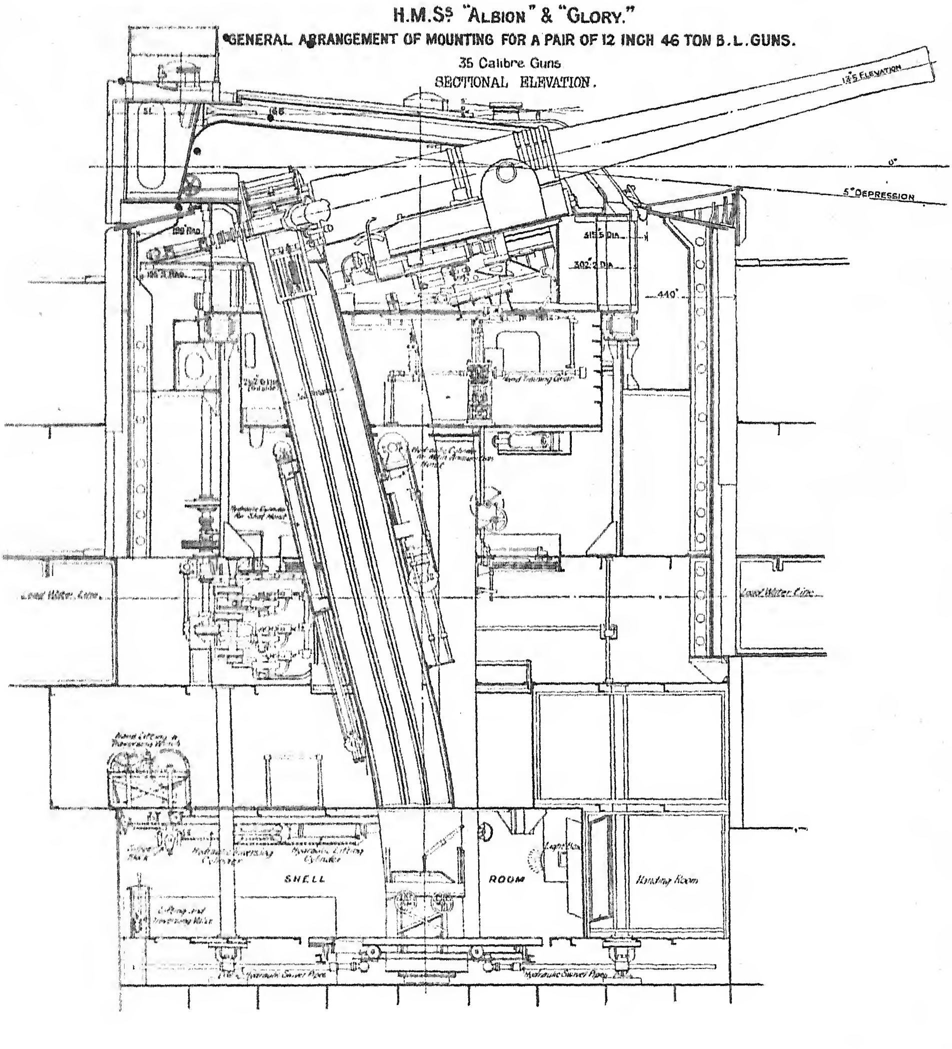
[Insert between Pl. XXIII. and XXV., pp. 520-21.

PLATE XXVI.

H.I.J.M Ss "FUJI" & "YASHIMA."

GENERAL ARRANGEMENT OF TURRET AND MOUNTING FOR 12 INCH B.L.GUNS.

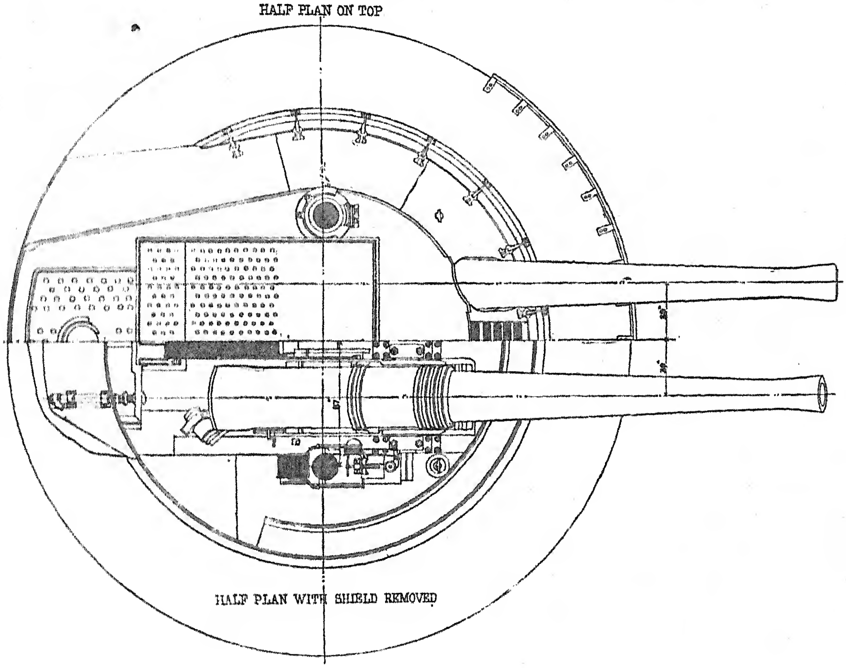



H.M.S? "ALBION" & "GLORY."
GENERAL ARRANGEMENT OF MOUNTING FOR A PAIR OF 12 INCH 46 TON B.L. GUNS.
35 Calibre Guns
SECTIONAL ELEVATION.
13½° ELEVATION
0°
5° DEPRESSION
515.5 DIA.
302.2 DIA.
440"
Load Water Line
SHELL
ROOM
Handing Room

H.M.S^{s} "ALBION" & "GLORY.

GENERAL ARRANGEMENT OF MOUNTING FOR A PAIR OF 12 INCH 46 TON B.L.GUNS

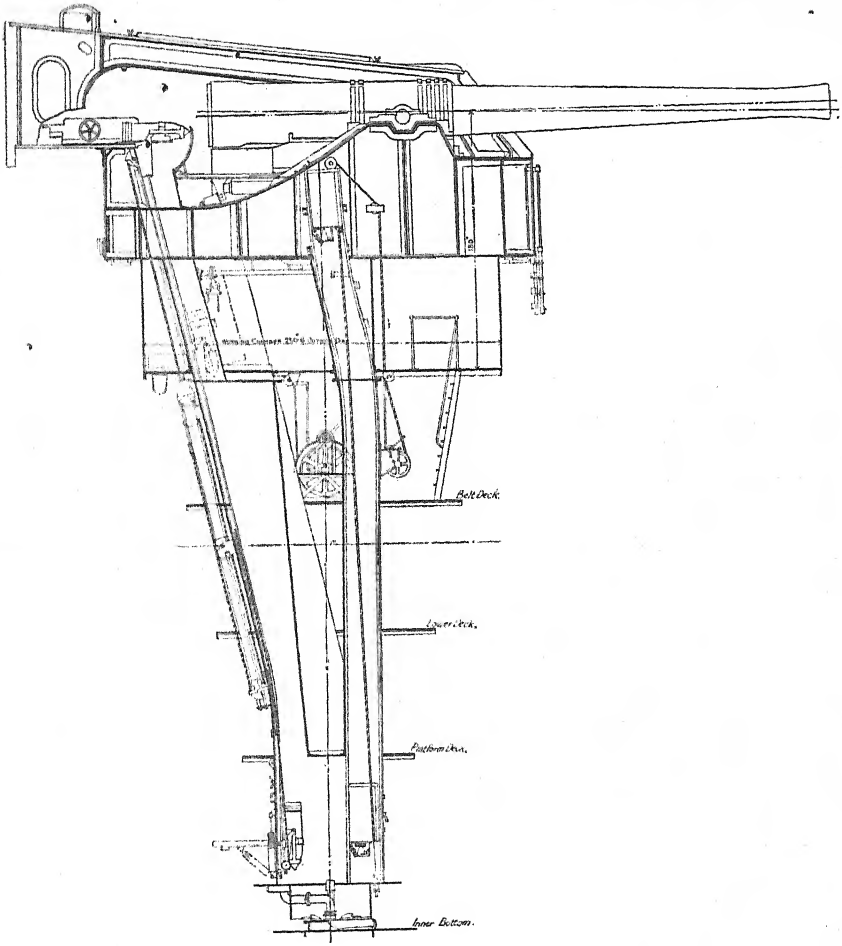
HALF PLAN ON TOP



HALF PLAN WITH SHIELD REMOVED

H.M.S^s "ALBION" & "GLORY."

SECTIONAL ELEVATION SHEWING ALTERNATIVE POWDER AND SHOT HOISTS.

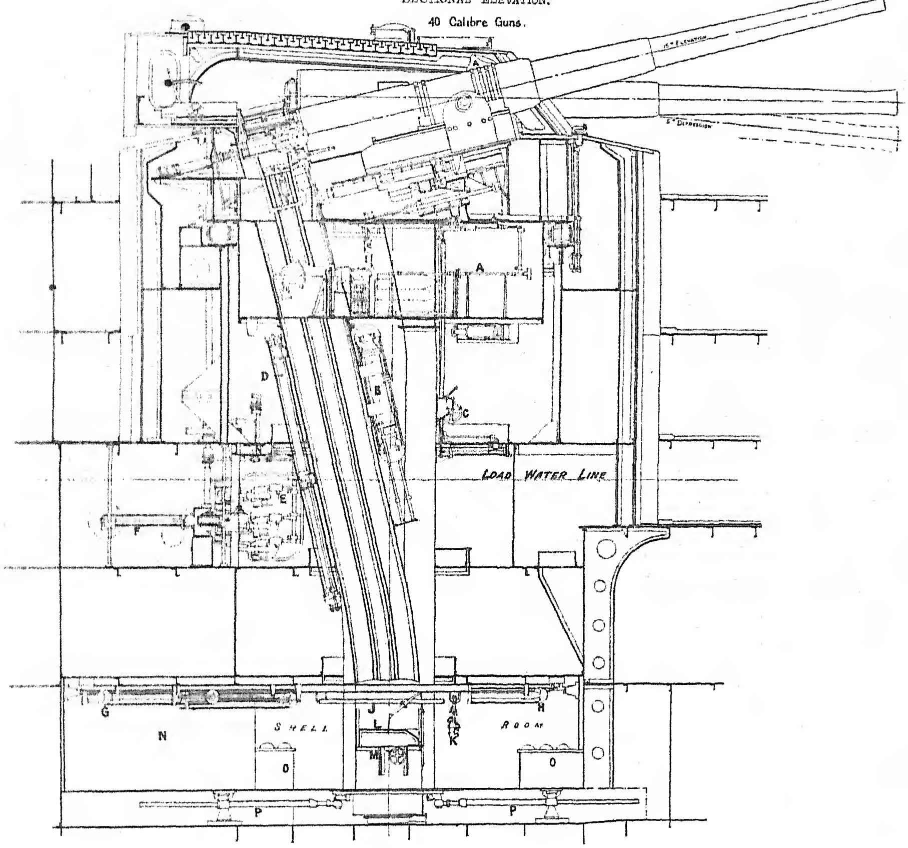


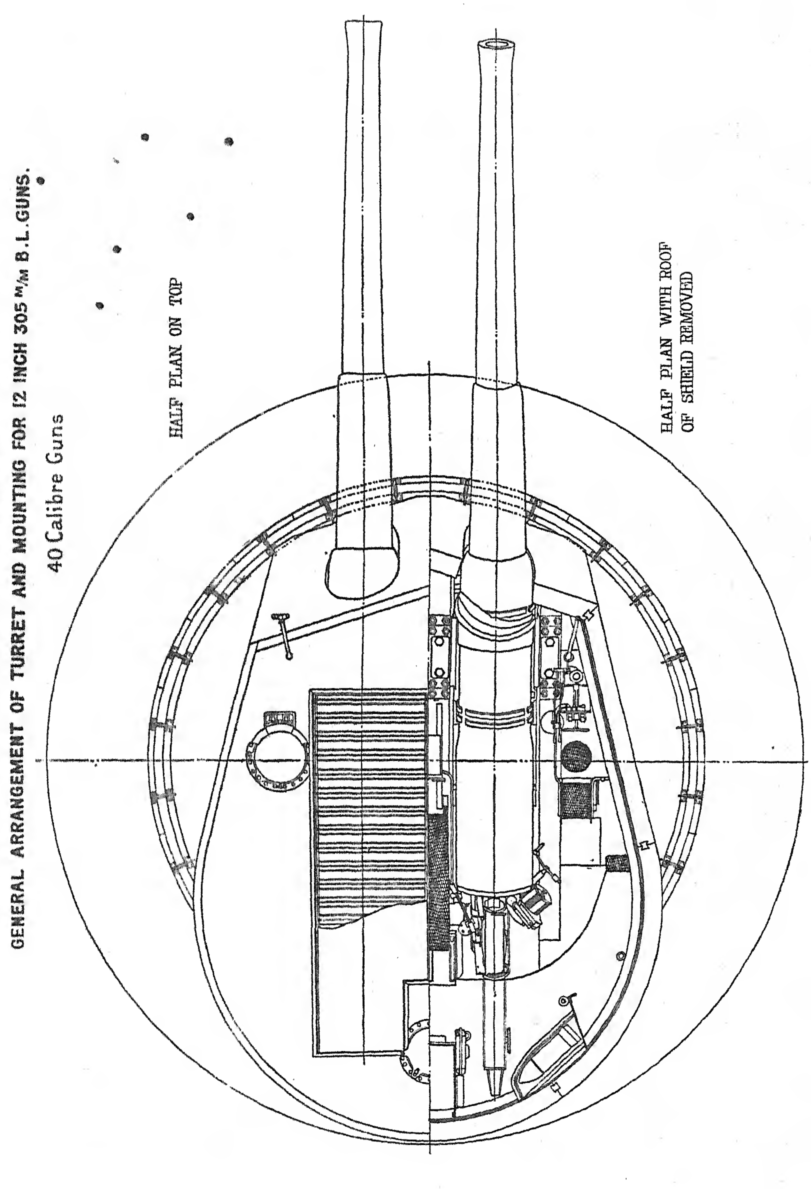
"SHIKISHIMA"

GENERAL ARRANGEMENT OF TURRET AND MOUNTING FOR 12 INCH 305 M/M B.L. GUNS.

SECTIONAL ELEVATION.

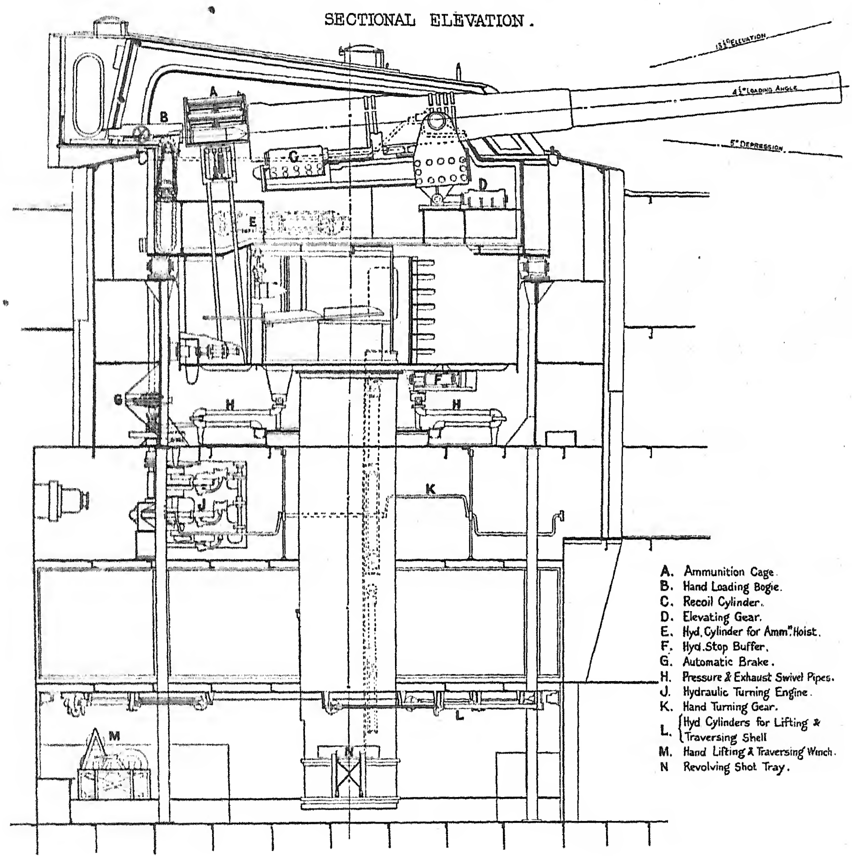
40 Calibre Guns.




H.I.J.M.S. "SHIKISHIMA."
GENERAL ARRANGEMENT OF TURRET AND MOUNTING FOR 12 INCH 305 M/M B.L. GUNS.
40 Calibre Guns
HALF PLAN ON TOP
HALF PLAN WITH ROOF
OF SHIELD REMOVED

H.M.S[s] "FORMIDABLE" & "IMPLACABLE."

GENERAL ARRANGEMENT OF TURRET AND MOUNTING FOR A PAIR OF 12 INCH 49 TON GUNS.

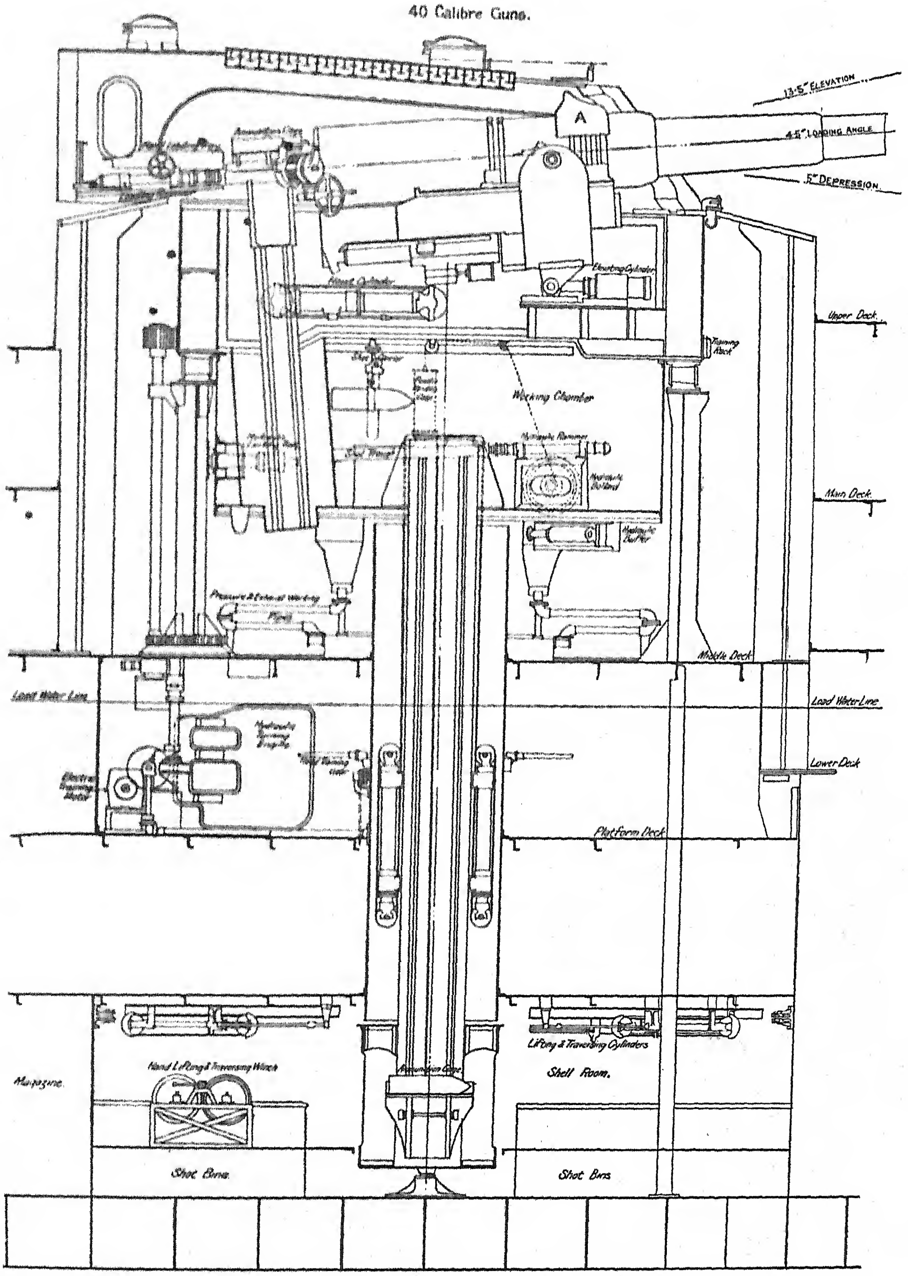


H.I.J.M.S "MIKASA".

GENERAL ARRANGEMENT OF TURRET AND MOUNTING FOR A PAIR OF 12 INCH 49 TON B.L. GUNS.

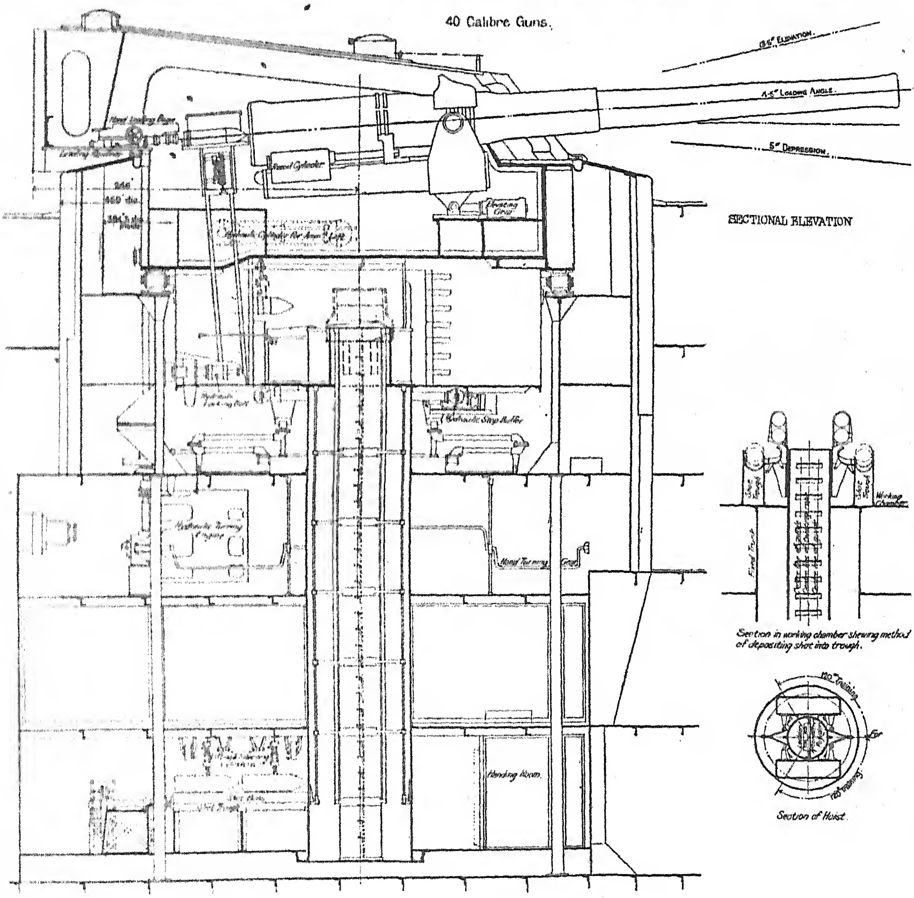
SECTIONAL ELEVATION

40 Calibre Guns.



[Inset between Pl. XXXII. and XXXIV., pp. 520-21.

DESIGN FOR MOUNTING TWO 12 INCH GUNS WITH CENTRAL HOIST WITH FLEXIBLE GUIDES.



DESIGN OF 12 INCH MAGAZINE AND SHELL ROOMS FOR CENTRAL HOIST WITH FLEXIBLE GUIDES.

SCALE $\frac{1}{75}$

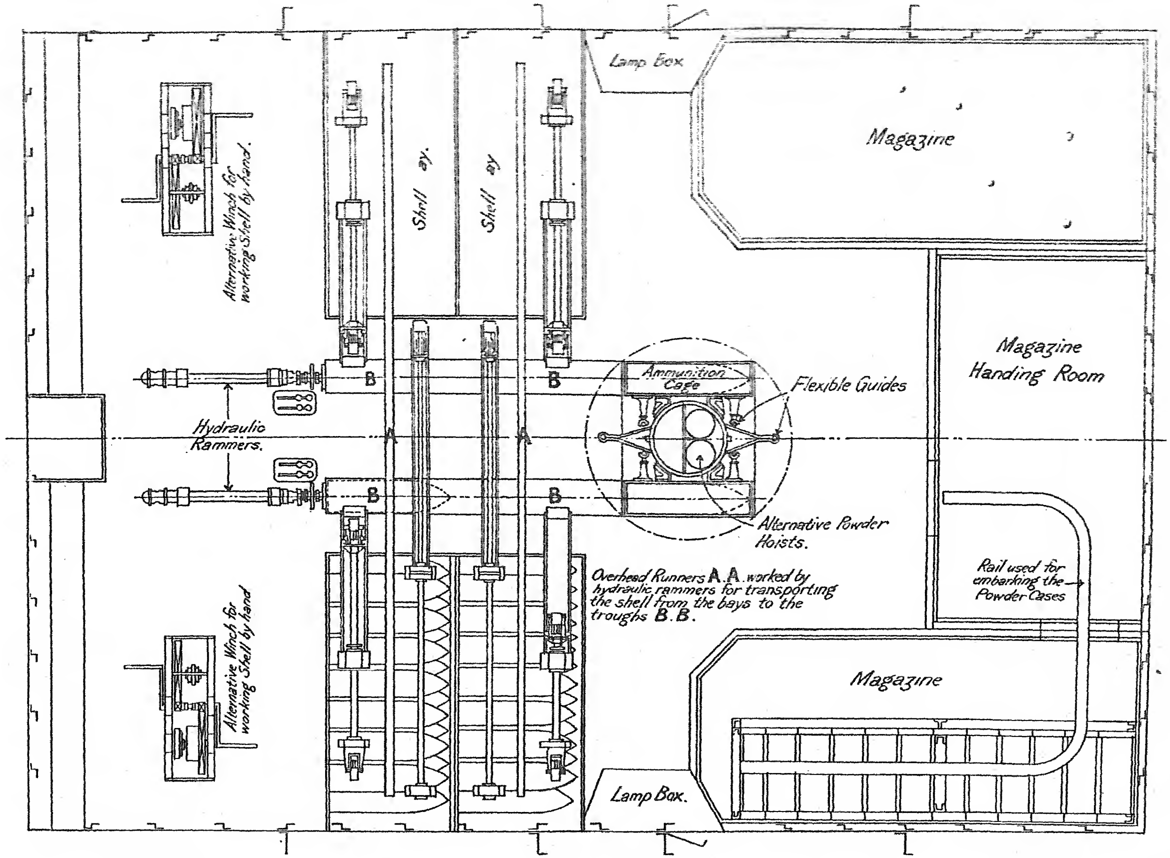


FIG. 3.

OVERHEAD RUNNER FOR CIRCULAR RAIL IN SHELL ROOM

SCALE $\frac{1}{10}$

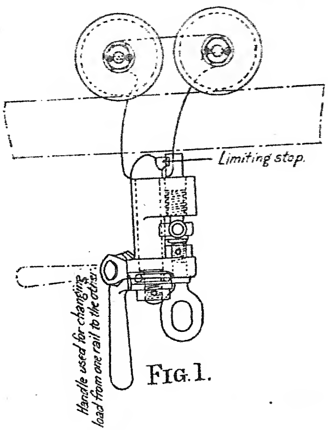


FIG. 1.

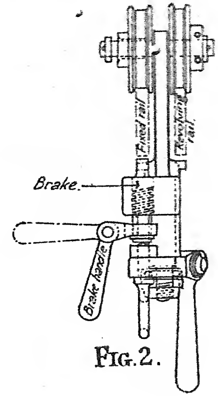
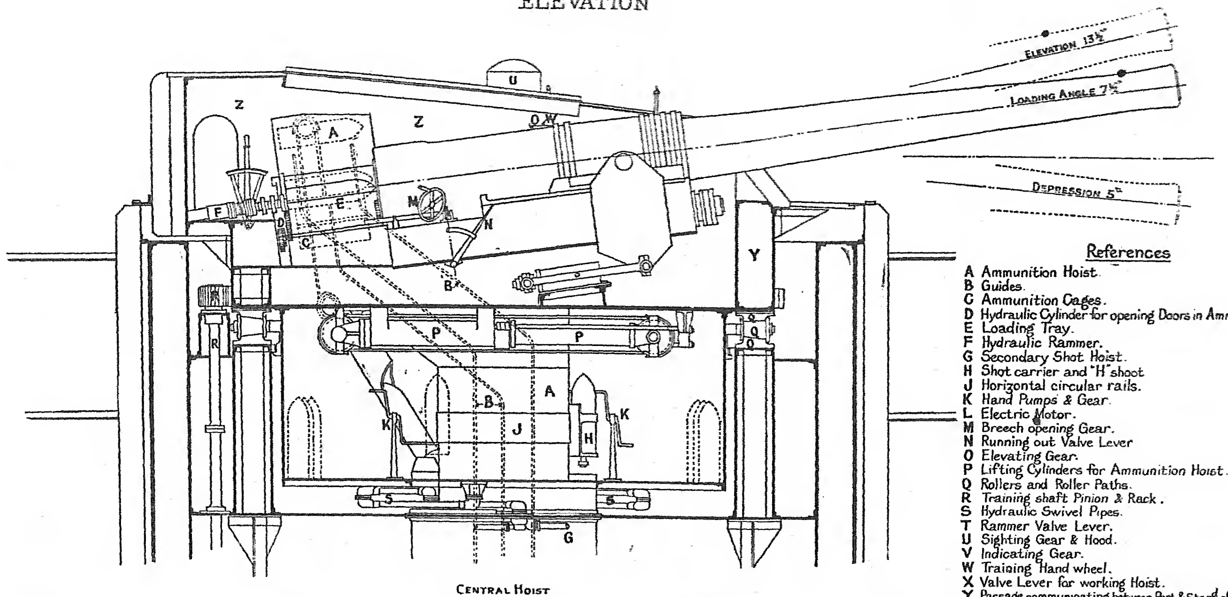


FIG. 2.

ARRANGEMENT OF TURRET AND MOUNTING FOR A PAIR OF 12 INCH 46 TON B. L. GUNS SHOWING CENTRAL FLEXIBLE GUIDE HOIST CONTINUED TO REAR OF THE GUNS.

35 Calibre Gun.

ELEVATION



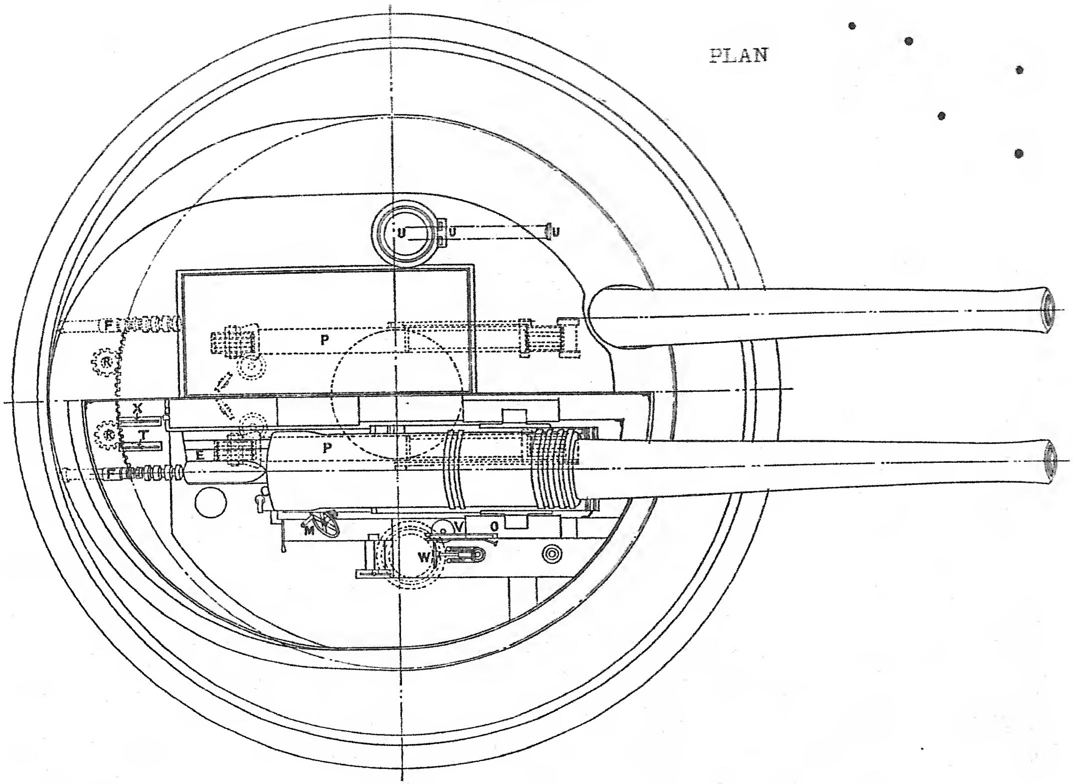
References

- A Ammunition Hoist.
- B Guides.
- C Ammunition Cages.
- D Hydraulic Cylinder for opening Doors in Ammn. Trunk.
- E Loading Tray.
- F Hydraulic Rammer.
- G Secondary Shot Hoist.
- H Shot carrier and "H" shoot
- J Horizontal circular rails.
- K Hand Pumps & Gear.
- L Electric Motor.
- M Breech opening Gear.
- N Running out Valve Lever
- O Elevating Gear.
- P Lifting Cylinders for Ammunition Hoist.
- Q Rollers and Roller Paths.
- R Training shaft Pinion & Rack.
- S Hydraulic Swivel Pipes.
- T Rammer Valve Lever.
- U Sighting Gear & Hood.
- V Indicating Gear.
- W Training Hand wheel.
- X Valve Lever for working Hoist.
- Y Passage communicating between Port & Stard. of Turntable
- Z Diaphragm separating Port & Stard. of Turntable

ARRANGEMENT OF TURRET AND MOUNTING FOR A PAIR OF 12 INCH 46 TON B.L. GUNS SHOWING CENTRAL FLEXIBLE GUIDE HOIST CONTINUED TO REAR OF THE GUNS.

35 Calibre Guns

PLAN



XV.

SOME MODERN EXPLOSIVES

(*Paper read at the Royal Institution*, 1900.)

Nearly thirty years ago, in the Royal Institution, I had the honour of describing the great advances which had then recently been made both in our knowledge of the phenomena which attend the decomposition of gunpowder, and in its practical application to the purposes of artillery.

I described the uncertainty which up to that date had existed as to the tension developed by its explosion, the estimates varying enormously from the 101,000 atmospheres (about 662 tons on the square inch) of Count Rumford to the 1000 atmospheres (6·6 tons per square inch) of Robins, or, taking more modern estimates, from the 24,000 atmospheres (158 tons per square inch) of Piobert and Cavalli to the 4300 atmospheres (about 29 tons per square inch) of Bunsen and Schischkoff.

These uncertainties were, I think I may say, set at rest by certain experiments carried out both in guns and close vessels at Elswick, by the labours of the Explosive Committee appointed by the War Office, and by researches conducted by Sir F. Abel and myself. These researches were conducted on a large scale, with the view of reproducing as nearly as possible in experiment the conditions that exist in the bore of the gun. You may judge of the magnitude of the experiments, when I tell you that I have fired and completely retained in one of my cylinders a charge of no less than 28 lbs. of ordinary powder.

The result of the discussion of the whole series of experiments led to the following conclusions:—

1. That the tension of the products of combustion at the moment of explosion when the powder practically filled the space in which it is fired—that is, when the density is about unity—is a little over 40 tons on the square inch, or about 6400 atmospheres.

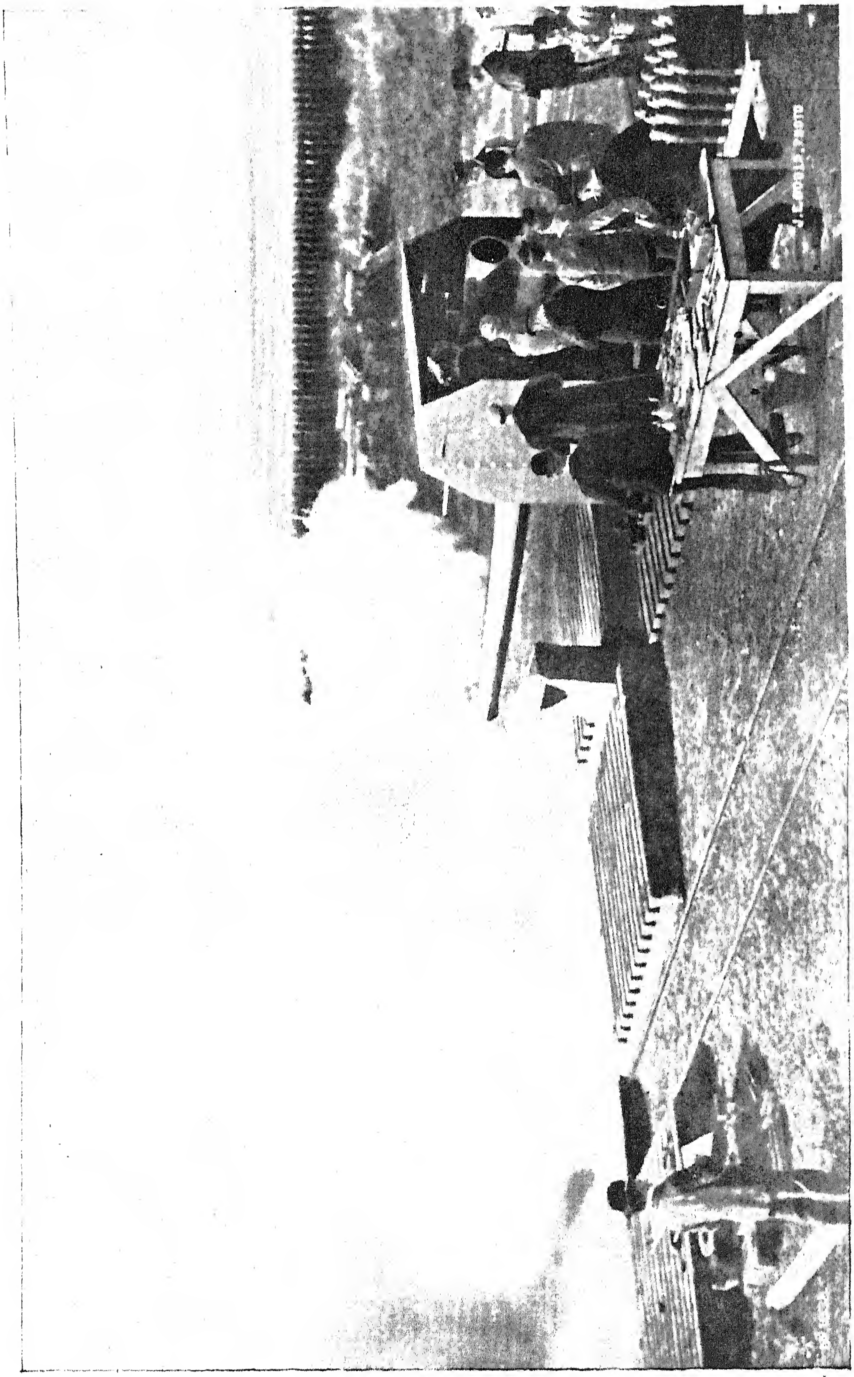
2. Although changes in the chemical composition of powder, and even changes in the mode of ignition, cause a very considerable change in the metamorphosis experienced in explosion, as evidenced by the proportions of the products, the quantity of heat generated, and the quantity of permanent gases produced, being materially altered, it is somewhat remarkable that the tension of the products in relation to the gravimetric density is not nearly so much affected as might be expected from the considerable alteration in the above factors.
3. The work that gunpowder is capable of performing in expanding in the bore of a gun was determined both by actual measurement and by calculation, and the results were found to accord very closely.
4. The total potential energy of exploded gunpowder supposed to be fired at the density of unity was found to be about 332,000 grm.-units per grm., or 486 foot-tons per pound of powder.

I must confess that when I gave the lecture I have referred to, seeing the many centuries during which gunpowder had held its own as practically the sole propelling agent for artillery purposes, seeing also that gunpowder differs in certain important points from the explosives to which I shall presently call your attention, I had serious doubts as to whether it would be possible so far to modify these latter as to permit of their being used in large charges and under the varied conditions required in the Naval and Military Services.

Gunpowder is not, like guncotton, cordite, nitro-glycerine, lyddite, and other similar explosives, a definite chemical combination in a state of unstable equilibrium, but is merely an intimate mixture of nitre, sulphur, and charcoal, in proportions which can be varied to a very considerable extent without striking differences in results. These constituents do not, during the manufacture of the powder, suffer any chemical change, and being a mixture it cannot be said under any condition truly to detonate. It deflagrates or burns with great rapidity, varying very largely with the pressure and other circumstances under which the explosion is taking place—a train like that to which I set fire taking, as you see, an appreciable time to burn, while in the bore of the gun a similar length of charge would be consumed in less that the hundredth part of a second.

You will further have observed the heavy cloud of smoke which

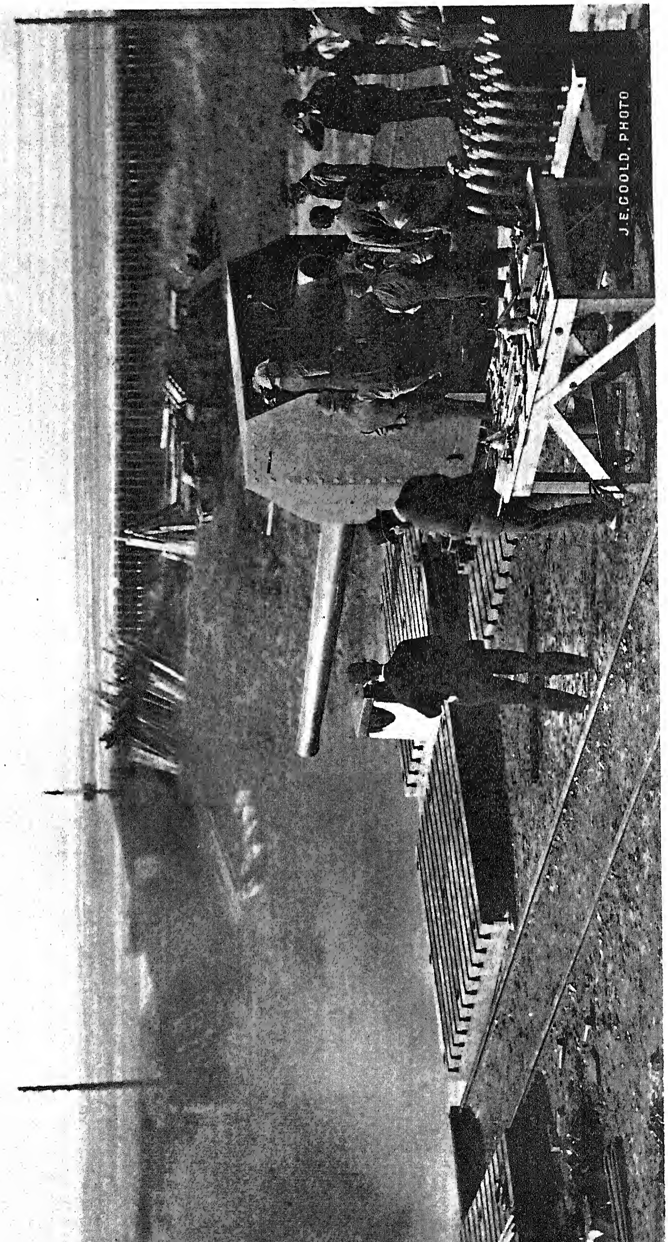
PLATE I.



9-INCH GUN FIRING BLACK POWDER.

To face p. 523.

PLATE II.



6-INCH GUN FIRING CORDITE.

[To face p. 523.

has attended the deflagration you have seen. Nearly six-tenths of the weight of the powder after explosion remains as a finely-divided solid, giving rise to the so-called smoke familiar to many of you, and of which a good illustration is shown in this instantaneous photograph, Plate I. By way of comparison, I burn similar lengths of guncotton in the form (1) of cotton, (2) of strand, (3) of rope, and you will observe the different rates at which these varied forms of the same material are consumed, the rate depending in this case upon the greater aggregation and higher density, consequently higher pressure of the successive samples.

Although the names of cordite and ballistite are probably familiar to all of you, the appearance may not be so familiar, and I have here on the table samples of the somewhat protean forms which these explosives, or explosives of the same nature, are made to assume.

Here, for instance, are forms of cordite, the explosive of the service, for which we are indebted to the labours of Sir F. Abel and Prof. Dewar. This, which is in the form of fine threads, is used in small arms, and here are successive sizes, adapted to successive larger calibres, until we reach this size which is that employed for the charge of the 12-inch 50-ton guns.

A couple of the smaller cords I burn, both for purposes of comparison and to draw your attention to the entire absence of smoke.

The smoke of the gunpowder you see still floating near the ceiling, but little or no trace of smoke can be seen from such explosives as guncotton, cordite, or ballistite, their products of combustion being entirely gaseous. See photograph, Plate II.

You will have observed that in the combustion which you have just seen there is no smoke, but I must explain, and I shall shortly show you, that this combustion is not quite the same as that which takes place, for instance, in the chamber of a gun. Here the carbonic oxide and hydrogen, which are products of explosion, burn in the air, giving rise, with the aid of a little free carbon, to the bright flame you see, and somewhat increasing the rate of combustion. In a gun, however, owing chiefly to pressure, the cordite is consumed in a very small portion of a second.

In order to illustrate the effect of pressure upon the rate of combustion, I venture to show you a very beautiful experiment devised by Sir F. Abel. It has been shown in this room before, but it will bear repetition.

In this globe there is a length of cordite. I pass a current

through the platinum wire on which it is resting, and you see the cordite burns. I now exhaust the air and repeat the experiment. The wire is red-hot, but the cordite will not burn. That the failure to burn is not due to the absence of oxygen, is shown by plunging lighted cordite into a jar of carbonic acid, where, although a match is instantly put out, the cordite continues to burn—but observe the difference. There is no longer any bright flame, although the cordite is being consumed at about the same rate as when burned in air; and when a sufficient quantity of the CO_2 is displaced, I can make the inflammable gases ignite and burn at the mouth of the jar.

Another illustration is also instructive. I have here a stick of cordite wrapped round with filter paper; I dip it in water and light the end; you may note that at first you see the bright flame. But, as the combustion retreats under the wet filter paper, there appears a space between the flame and the cordite, the flame finally disappears, hot gases with sparks of carbon alone showing.

One other pretty experiment I show. I have here a stick of cordite, which I light. When fairly lighted, I plunge it in this beaker of water. The experiment does not always succeed at the first attempt, but you now see the cordite burning under the water much as it did in the jar of carbonic acid. The red fumes you observe are due to the formation of nitric peroxide caused by the decomposition of the water by the heat.

I have on the table samples of certain other smokeless explosives of the same class. Here is a ballistite used in Italy. Here is some Norwegian ballistite. Here again is ballistite in the tubular form, and in these bottles it is seen in the form of cubes. Here is some gelatinised guncotton in the tubular form, and here are some interesting specimens with which I have experimented, and which up to a certain pressure gave good results, but which exhibited some tendency to violence when that pressure was exceeded. Here also are some samples of the French B. N. powder, consisting of nitrocellulose partially gelatinised and mixed with tannin, and with barium and potassium nitrates. Lastly, I show you here a sample of picric acid, a substance which has been used for many years as a colouring material, but which will be of interest to you, because it is used as the explosive of lyddite shell, concerning which I shall presently have more to say; it differs from all the other explosives in being, in the crystalline form, exceedingly difficult to light. I fuse, however, in this porcelain crucible a small quantity. I pour a little on a slab, and on dropping a fragment into a red-hot test-tube

you see with how much violence the fragment explodes. I also burn a small quantity, and you will observe that, unlike guncotton, cordite, and ballistite, it is not free from smoke, the smoke in this case being simply carbonaceous matter. You will observe also how much more slowly it burns.

The composition of these various explosives (although in the case of both cordite and ballistite I have experimented with samples differing widely in the proportion of their ingredients), may be thus stated:—

The guncotton I employed was of Waltham-Abbey manufacture, and when dried consisted of 4·4 per cent. of soluble cotton and 95·6 per cent. of insoluble—as used, it contained 2·25 per cent. of moisture.

The service cordite consists of 37 per cent. trinitro-cellulose with a small proportion of soluble guncotton, 58 per cent. of nitro-glycerine, and 5 per cent. of the hydro-carbon vaseline.

The ballistite I principally used was composed of 50 per cent. dinitro-cellulose (collodion cotton) and 50 per cent. of nitro-glycerine. The whole of the cellulose was soluble in ether alcohol, and the ballistite was coated with graphite.

The French B. N. powder consisted of nitro-cellulose partly gelatinised, and mixed with tannin, with barium and potassium nitrates. The transformation experienced by some of these explosives is given in Table 1, while the pressures in relation to the gravimetric densities of some of the more important are shown in Fig. 1.

TABLE 1.

Constituents.	Cordite.	Ballistite.	B. N.	Lyddite.
	Vols.	Vols.	Vols.	Vols.
CO_2	20·5	29·1	21·1	12·8
CO	23·3	21·4	24·2	49·7
H	16·5	15·0	16·4	13·8
N	14·6	10·1	12·6	19·6
H_2O	23·6	24·4	25·0	3·8
CH_4	1·5	trace	0·6	0·3
Quantity of gas in c.c. per gramme	890·5	807	822	960·4
Units of heat . .	1272	1365	1003	856·3

The decomposition experienced by these high explosives on being fired is of much greater simplicity than that experienced by the old powders, and is moreover not subject to the considerable fluctuations in the ultimate products exhibited by them.

The products of explosion of guncotton, cordite, ballistite, etc.,

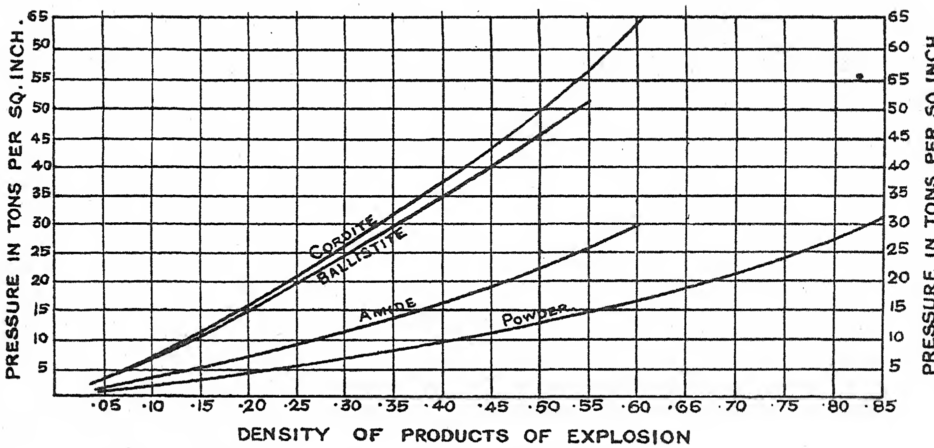
are at the temperature of explosion entirely gaseous, consisting of carbonic anhydride, carbonic oxide, hydrogen, nitrogen, and aqueous vapour, with generally a small quantity of marsh-gas.

The water collected, after the explosion-vessel was opened, always smelt, occasionally very strongly, of ammonia, and an appreciable amount was determined in the water.

In examining the gaseous products of the explosion of various samples of gunpowder, it was noted that as the pressure under which the explosion took place increased, the quantity of carbonic anhydride also increased, while that of carbonic oxide decreased. The same

Fig 1.

PRESSURES OBSERVED IN CLOSED VESSELS WITH VARIOUS EXPLOSIVES.

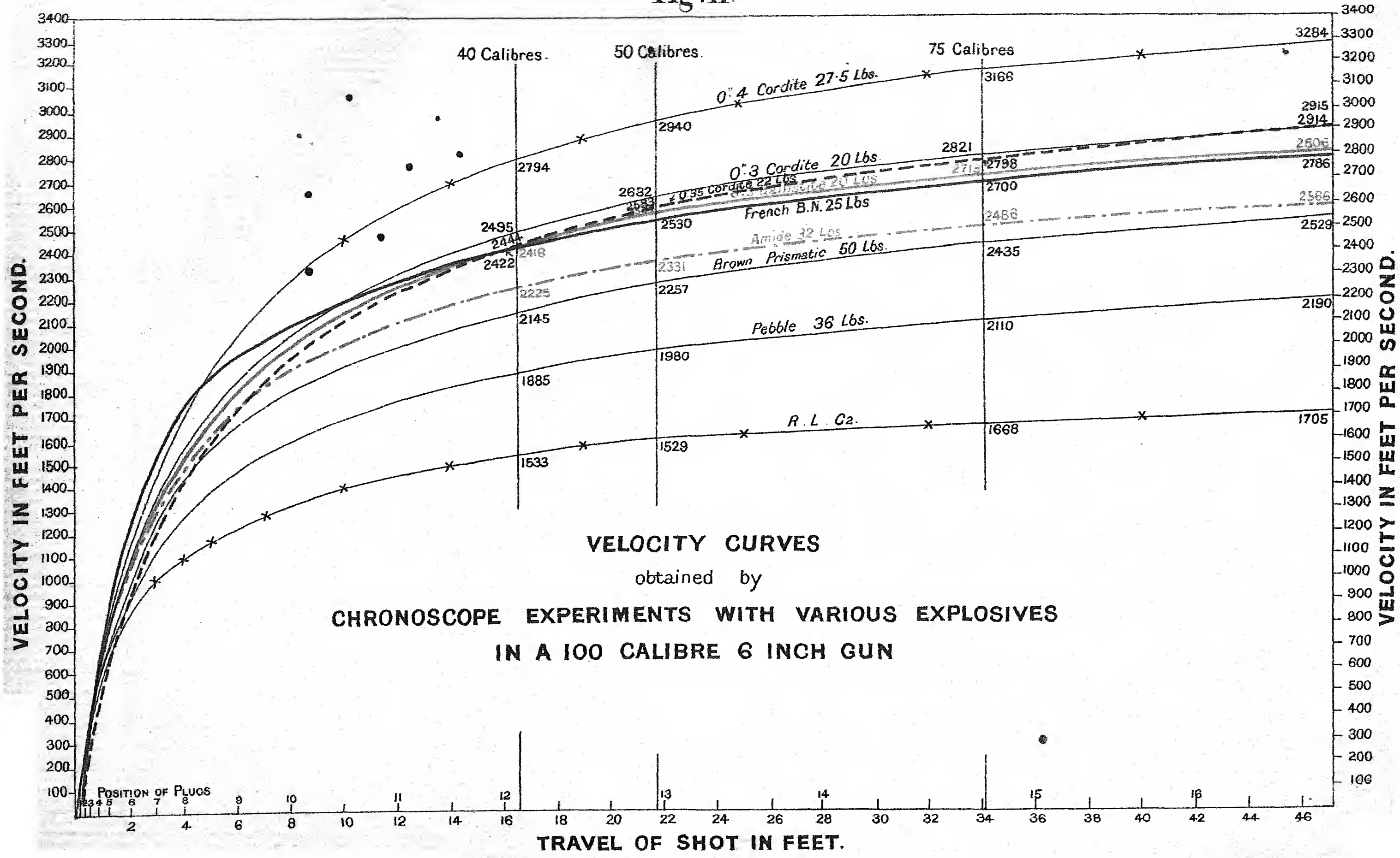


peculiarity is exhibited by all the explosives with which I have experimented. I show in Table 2, p. 527, the result of a very complete series of a sample of guncotton fired under varying pressures, and it will be noted that the volumes of carbonic oxide and carbonic anhydride are, between the highest and lowest pressures, nearly exactly reversed.

There are slight changes as regards the other products, but they do not compare in importance with that to which I have referred.

But before drawing your attention to other points of interest, it is desirable to give you an idea of the advances in ballistics which have been made, both by improvements in the manufacture of the old powders and by the introduction of the new.

Fig. II.


VELOCITY CURVES
obtained by
CHRONOSCOPE EXPERIMENTS WITH VARIOUS EXPLOSIVES
IN A 100 CALIBRE 6 INCH GUN
VELOCITY IN FEET PER SECOND.
TRAVEL OF SHOT IN FEET.
POSITION OF PLUGS
40 Calibres.
50 Calibres.
75 Calibres
0".4 Cordite 27·5 Lbs.
0".3 Cordite 20 Lbs
French B.N. 25 Lbs
Amide 32 Lbs
Brown Prismatic 50 Lbs.
Pebble 36 Lbs.
R. L. G2.
2794
2495
2444
2422
2416
2225
2145
1885
1533
2940
2632
2530
2331
2257
1980
1529
2821
2798
2700
2488
2435
2110
1668
3166
3284
2915
2914
2786
2566
2529
2190
1705

On Fig. II. are placed the results as regards velocity of nine explosives, commencing with the R. L. G_2 powder, which was in use in the latter part of the fifties, and terminating with the cordite of the present day.

TABLE 2.

Constituents.	Under pressure of Explosion, tons per square inch.						
	2 tons.	8 tons.	12 tons.	18 tons.	20 tons.	45 tons.	50 tons.
Vols.							
CO_2 . . .	21·44	25·06	26·27	27·21	26·75	28·13	29·27
CO . . .	29·66	26·31	25·08	25·24	24·53	23·19	22·31
H	15·92	15·33	16·03	14·56	14·77	14·14	13·56
N	13·63	13·80	13·22	13·13	13·43	12·99	13·07
H_2O . . .	19·09	19·09	19·09	19·09	19·09	19·09	19·09
CH_4 . . .	·26	·41	·31	·77	1·47	2·46	2·70

The experiments I am now referring to were made in a gun of 100 calibres in length, and were so arranged that in a single round the velocities could be measured at 16-points of the bore. The chronoscope with which these velocities were taken has been already described, and I will now only say that it is capable of registering time to the millionth of a second with a probable error of between two and three millionths. One curious fact connected with the mode of registration I may mention. In the early experiments with the old powders, where the velocities did not exceed 1500 or 1600 feet per second, the arrangement for causing the projectile to record the time of its passing any particular point was effected by the shot knocking down a small steel knife or trigger which projected slightly into the bore, but when the much higher velocities, with which I subsequently experimented, were employed, this plan was found to be unsatisfactory, the steel trigger, instead of being immediately knocked down by the shot, frequently preferred, instead, to cut a groove in the shot, sometimes nearly its whole length, before it acted. Hence another arrangement for cutting the primary wires had to be adopted.

The diagram I am now showing you is, however, both interesting and instructive. The intention, among other points, was to ascertain, for various calibres in length in a 6-inch gun, the velocities and energies that could be obtained, the maximum pressures, whether mean or wave, not exceeding about 20 tons on the square inch. The horizontal line or axis of abscissæ represents the travel of the shot

in feet, the ordinates or perpendiculars from this line to the curve represents the velocity at that point.

The lowest curve on the diagram gives, under the conditions I have mentioned, the velocities attainable with the powder which was used when rifled guns were first introduced into the service, and you will note that with this powder the velocity attained with 100 calibres was only 1705 feet per second, while with 40 calibres it was 1533 feet per second. Next on the diagram comes pebble-powder, with a velocity of 2190 feet per second; next comes brown prismatic, with a velocity of 2529 feet per second.

The next powder is one of considerable interest, and one which might have risen to importance had it not been superseded by explosives of a very different nature. It is called amide powder, and in it ammonium nitrate is substituted for a large portion (about half) of the potassium nitrate, and there is also an absence of sulphur. You will observe the velocity in the 100-calibre gun is very good, 2566 feet per second. The pressure also was low, and free from wave action. It is naturally not smokeless, but the smoke is much less dense, and disperses much more rapidly than does the smoke of ordinary powder. Its great advantage, however, was, that it eroded steel very much less than any other powder with which I experimented, while its great disadvantage was due to the deliquescent properties of ammonium nitrate, necessitating the keeping of the cartridges in air-tight cases.

Next on the diagram comes B. N. or Blanche Nouvelle powder, an explosive which, while free from wave action, is remarkable, as you will note if you follow the curve, in developing a much higher velocity than the other powders in the first few feet of motion, and less in the later stages of expansion.

Thus, if you compare this curve with the highest curve on the diagram, that of the four-tenths cordite, you will note that the B. N. curve for the first eight feet of motion is the higher, and that at about eight feet the curves cross, the B. N. giving a final velocity of 2786 feet per second, or 500 feet below the cordite curve.

Then follows ballistite, which, with much lower initial pressure, gives a velocity of 2806 feet per second, or somewhat higher than that of B. N. Then follow three different sizes of cordite, the highest of which gives a muzzle velocity of 3284 feet per second, or a velocity nearly double that of the early R. L. G_2.

In the somewhat formidable-looking table (Table 3) I have placed on the wall, are exhibited the velocities and energies

realised in a 6-inch gun with the various explosives I have named, and the table, in addition, shows the velocities and energies in guns of the same calibre but of 40, 50, and 75 calibres in length, as well as in that of 100 calibres.

TABLE 3.—*6-inch gun,* 100 *calibres long. Velocities and energies realised with high explosives. Weight of projectile,* 100 *lbs.*

Nature and weight of explosive.	Length of bore, 40 calibres.		Length of bore, 50 calibres.		Length of bore, 75 calibres.		Length of bore, 100 calibres.	
	Velocity.	Energy.	Velocity.	Energy.	Velocity.	Energy.	Velocity.	Energy.
	F. S.	F. T.	F. S.	F. T.	F. S.	F. T.	F. S.	F. T.
Cordite, ·4 in. (27·5 lbs.)	2794	5413	2940	5994	3166	6950	3284	7478
Cordite, 0·35 in. (22 lbs.)	2444	4142	2583	4626	2798	5429	2915	5892
Cordite, 0·3 in. (20 lbs.)	2495	4316	2632	4804	2821	5518	2914	5888
Ballistite, 0·3 in. cubs. (20 lbs.) . . .	2416	4047	2537	4463	2713	5104	2 806	5460
French B. N. (25 lbs.) .	2422	4068	2530	4438	2700	5055	2786	5382
Amide prism (32 lbs.) .	2225	3433	2331	3768	2486	4285	2566	4566
Brown prism (50 lbs.) .	2145	3190	2257	3532	2435	4111	2529	4485
Pebble-powder (36 lbs.)	1885	2464	1980	2718	2110	3087	2190	3326
R. L. G.$_2$ (23 lbs.) . .	1533	1630	1592	1757	1668	1929	1705	2016

If you compare the results shown in the highest and lowest lines of this table, that is, the results given by the highest and lowest curves on the diagram, you will see that the velocity of the former is nearly twice as great as that of the latter, while its energy and capacity for penetration is nearly four times as great.

I need hardly remind most of you that in artillery matters it is the energy developed, not the velocity alone, that is of vital importance. I venture to insist upon this point, because so many of those who desire to instruct the authorities, write as if velocity were the only point to be considered. In a given gun with a given charge, if the weight of the shot, within reasonable limits, be made to vary, the ballistic advantage is greatly on the side of the heavier shot, and for three principal reasons:—

1. More energy is obtained from the explosive.

2. Owing to the lower velocity, the resistance of the air is greatly reduced.

3. The heavier shot has greater capacity for overcoming the reduced resistance.

You will observe that on this velocity diagram, upon which I have kept you so long a time, is shown, not only the travel of the shot in feet, but the position of the plugs which gave the velocities.

Further, on the higher and lower curves, the observed velocities are shown where it is possible to do so. Near the origin of motion the points are so close that it is not possible to insert them without confusing the diagram.

At the risk of fatiguing you, I show, in Fig. III., curves showing the pressure existing in the bore at all points, these pressures being deduced from the curves of velocity.

You will note the point to which I drew your attention, with regard to the powder called B. N. You will remember that in the early stages of motion it gave velocity to the shot, much more rapidly than did the other powders. You see the effect in the pressure curves, the maximum being considerably higher than any of the other pressures, while the pressure towards the muzzle is, on the other hand, considerably below the average.

I fear you may think I have kept you unnecessarily long with these somewhat dry details, but I have had reasons for so doing.

In the first place I desire to demonstrate to you the enormous advances which have been made in artillery by the introduction of the new explosives, and which we in a great measure owe to the distinguished chemists and physicists who have occupied themselves with these important questions.

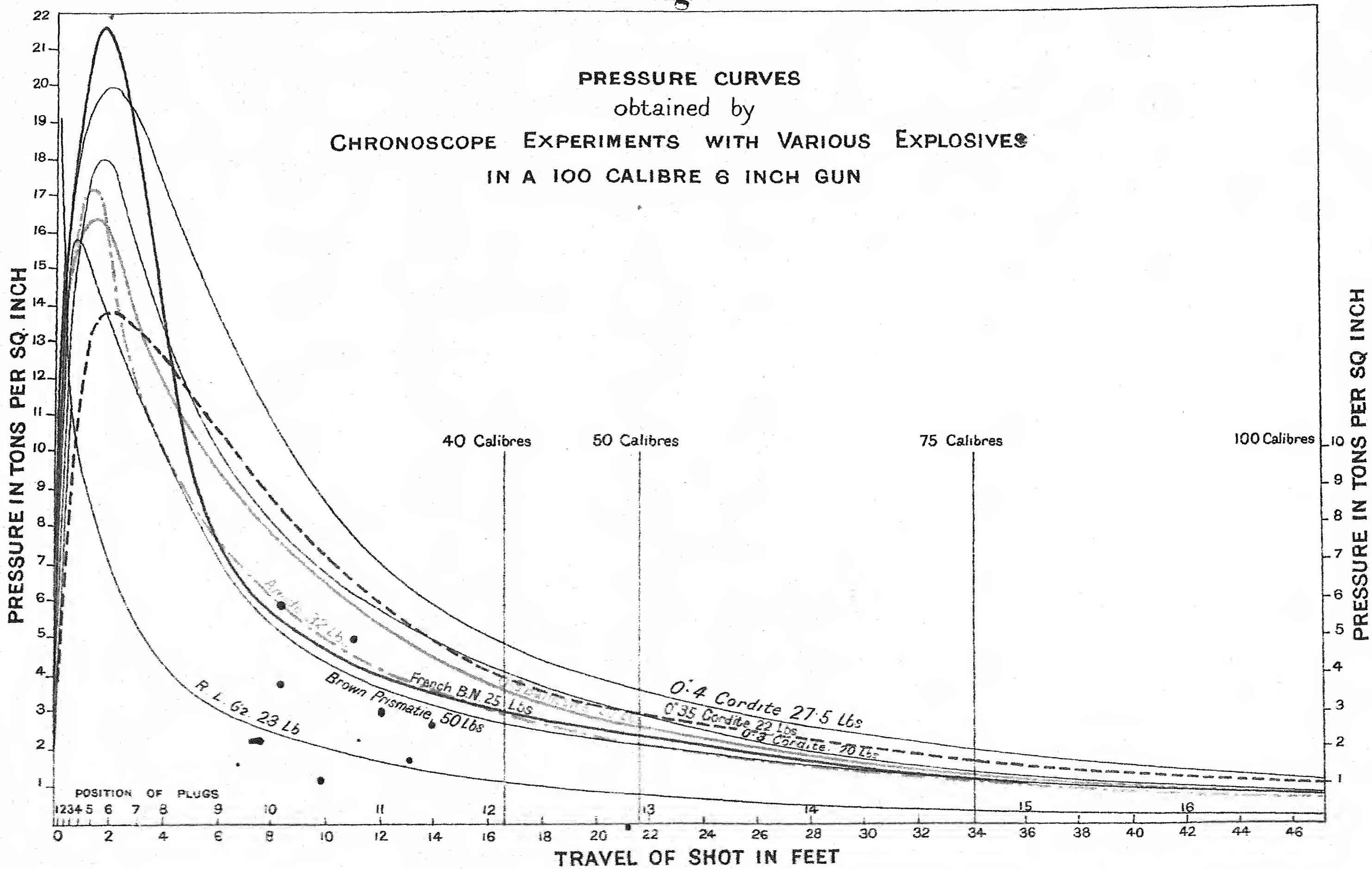
Secondly, I desire to show you that the explosive which has been adopted by this country, and which we chiefly owe to the labours of Sir F. Abel and Prof. Dewar, is in ballistic effect inferior to none of its competitors. I might go further, and say that it is decidedly superior.

Lastly, at a time when the efficiency of all our arms, and especially our artillery, is a question which has been deeply agitating the country, I may do some good by pointing out that the authorities are well aware that any practicable velocity or energy they may desire for their guns is at their disposal.

They have such guns, I mean guns with high velocity and high energy—whether they have enough of them, and whether they are always in the right place, is another matter, for which perhaps the military authorities are not altogether responsible. But velocity and energy is not the only thing that is required under all circumstances in war, and I ask you to believe that if the War Office authorities have, for their field guns, fixed on a velocity very much below what is possible, they have had sound and sufficient reasons for so doing.

My firm and I, individually, have had much to do with the introduction of the larger high-velocity and quick-firing guns into

Fig. III.


PRESSURE CURVES
obtained by
CHRONOSCOPE EXPERIMENTS WITH VARIOUS EXPLOSIVES
IN A 100 CALIBRE 6 INCH GUN
PRESSURE IN TONS PER SQ. INCH
PRESSURE IN TONS PER SQ INCH
TRAVEL OF SHOT IN FEET
POSITION OF PLUGS
40 Calibres
50 Calibres
75 Calibres
100 Calibres
0·4 Cordite 27·5 Lbs
0·35 Cordite 22 Lbs
0·3 Cordite 70 Lbs
French B.N. 25 Lbs
Brown Prismatic 50 Lbs
R. L. G2 23 Lb

our own and other services; but as an old artillery officer, in no way responsible for our field guns, I may perhaps be allowed to say that, whether as regards *matériel* or *personnel*, our field artillery is inferior to none anywhere, and I venture to add that in the present war it appears to have been handled in a way worthy of the reputation of the corps.

I fear the causes of some of our military failures at the commencement of the war must be looked for in other directions, and the present unfortunate war will turn out to be a blessing in disguise, if it should awaken the empire to the necessity of correcting serious defects in our organisation, possibly the natural result of our Constitution, and in that case the invaluable lives that have been lost will not have been sacrificed in vain.

I now pass to points which have to be considered when weighing the comparative merits of explosives for their intended ends.

You will easily understand that between explosives which are intended to be used for propelling purposes, and those which are intended to be used, say for bursting shell, a wide difference may exist.

In the former case, facility of detonation would be an insuperable objection; in the latter, the more perfect the detonation the better, certain special cases, to which I have not time to refer, excepted.

There exists, I think, considerable diversity of opinion as to what does, and what does not, constitute true detonation. I find many persons speak of a detonation, when I should merely consider that a very high pressure had been reached. This guncotton slab on the table affords me, I think, a fair opportunity of explaining my meaning. Were I to set fire to it, except for the large volume of flame and the great amount of heat generated, we in this room would not suffer; we should probably experience more inconvenience did I fire a similar slab of gunpowder, as detached burning portions would probably be projected to some distance.

But if I fired this same slab with two or three grammes of fulminate of mercury, a detonation of extreme violence would follow. The detonation would be capable of blowing a hole in a tolerably thick iron plate, and would probably put an end to a considerable proportion of the managers in the front row.

I mentioned to you some time ago the time in which a charge would be consumed in the chamber of a gun—if a charge of 500 lbs. of these slabs were effectively detonated, this charge would be con-

verted into gas in less than the twenty-thousandth part of a second.

No such result would follow were I to try a similar experiment with a slab of compressed gunpowder of the same dimensions. I do not say the experience would be pleasant, but there would be nothing of the instantaneous violent action which marks the decomposition of the guncotton.

To give you an idea of the extraordinary violence which accompanies detonation, I have fired, for the purpose of this lecture, with fulminate of mercury, a charge of lyddite in a cast-iron shell, and those who are sufficiently near, can see for themselves the result. By far the greater part of the cast-iron shell, weighing about 10 lbs., is reduced to dust, some of which is so fine that I assumed it to be deposited carbon until I had tested it with a magnet. I may add that the indentation of the steel vessel by pieces of the iron which were not reduced to powder, would appear to indicate velocities of not less than 1200 feet per second, and this velocity must have been communicated to the fragments in a space of less than 2 inches.

For the sake of comparison, I place beside it a cast-iron shell burst by gunpowder. You will observe the extraordinary difference. I also have on the table two small steel shells exploded, one by a perfectly detonated the other by a partially detonated charge. I may remark that in the accounts of the correspondents from the seat of war, frequent mention is made of the green smoke of lyddite. This appearance is probably due to imperfect detonation—to a mixture, in fact, of the yellow picric with the black smoke; I do not say, however, that imperfect detonation is necessarily an evil.

To another experiment I draw your attention.

For certain purposes, I caused to be detonated in the chamber of a 12-pr. a steel shell charged with lyddite. The detonation was not perfect, but the base of the shell was projected with great violence against the breech screw. You may judge of how great that violence was, when I tell you that the base of the shell took a complete impression of the recess for the primer, developing great heat in so doing; but what was still more remarkable, the central portion of the base also sheared, passing into the central hole through which the striker passes. This piece of shell is upon the table, and open to your inspection.

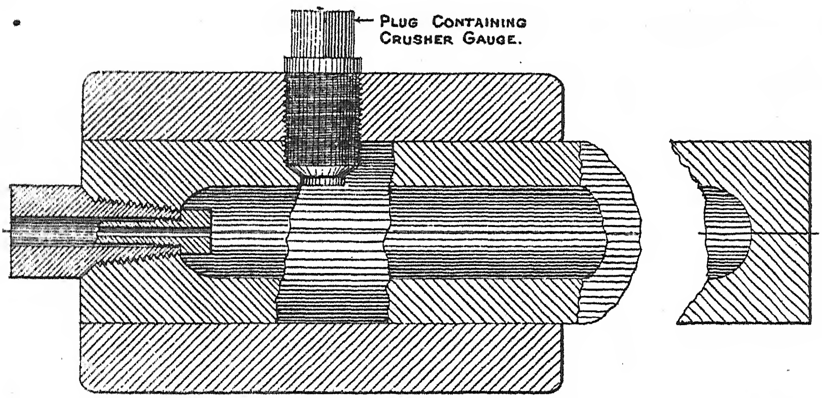
One other instance, to illustrate the difference between combustion and detonation, I trouble you with. Desiring to ascertain the

difference, if any, in the products of explosion between combustion and detonation, I fired a charge of lyddite in such a manner that detonation did not follow. The lyddite merely deflagrated. But a similar charge, differently fired, shortly afterwards detonated with such extreme violence as to destroy the vessel in which it was exploded. The manner in which the vessel failed I now show you (Fig. IV.), and I have on the table the internal crusher-gauge which was used, and which was also totally destroyed.

The condition of this gauge is very remarkable, and the action on the copper cylinder employed to measure the pressure was one to

FIG. IV.

EXPLOSION VESSEL



which I have no parallel in the many thousand experiments I have made with these gauges. The gauge itself is fractured in the most extraordinary way, even in some places to which the gas had no access, and the copper cylinder, which when compressed usually assumes a barrel-like form (that is with the central diameter larger than that at the ends, as shown in the diagram, Fig. V.), in this experiment, and in this only, was bulged close to the piston, as you see. It would appear as if the blow was so suddenly given that the laminæ of the metal next the piston endeavoured to escape in the direction of least resistance, that being easier than to overcome the inertia of the laminæ below.

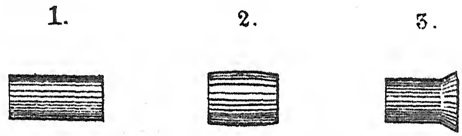
The erosive effect of the new explosives is another point of

first-rate importance in an artillery point of view. The cordite of the service is not, if the effect be estimated in relation to the energy impressed on the projectiles, more erosive than, for example, brown prismatic, which was itself a very erosive powder; but as we are able to obtain, as you have seen, very much higher energies with cordite than with brown prismatic, the erosion of the former is, for a given number of rounds, materially higher.

There is, however, one striking difference: by the kindness of Colonel Bainbridge, the Chief Superintendent of Ordnance Factories, I am enabled to show you a section of the barrel of a large gun eroded by 137 rounds of gunpowder. Beside it is a barrel of a 4·7-inch quick-firing gun eroded by 1087 rounds of gunpowder, and another eroded by 1292 rounds of cordite. You will observe the difference. In the former case the erosion much resembles a

Fig V.

COPPER CYLINDERS.



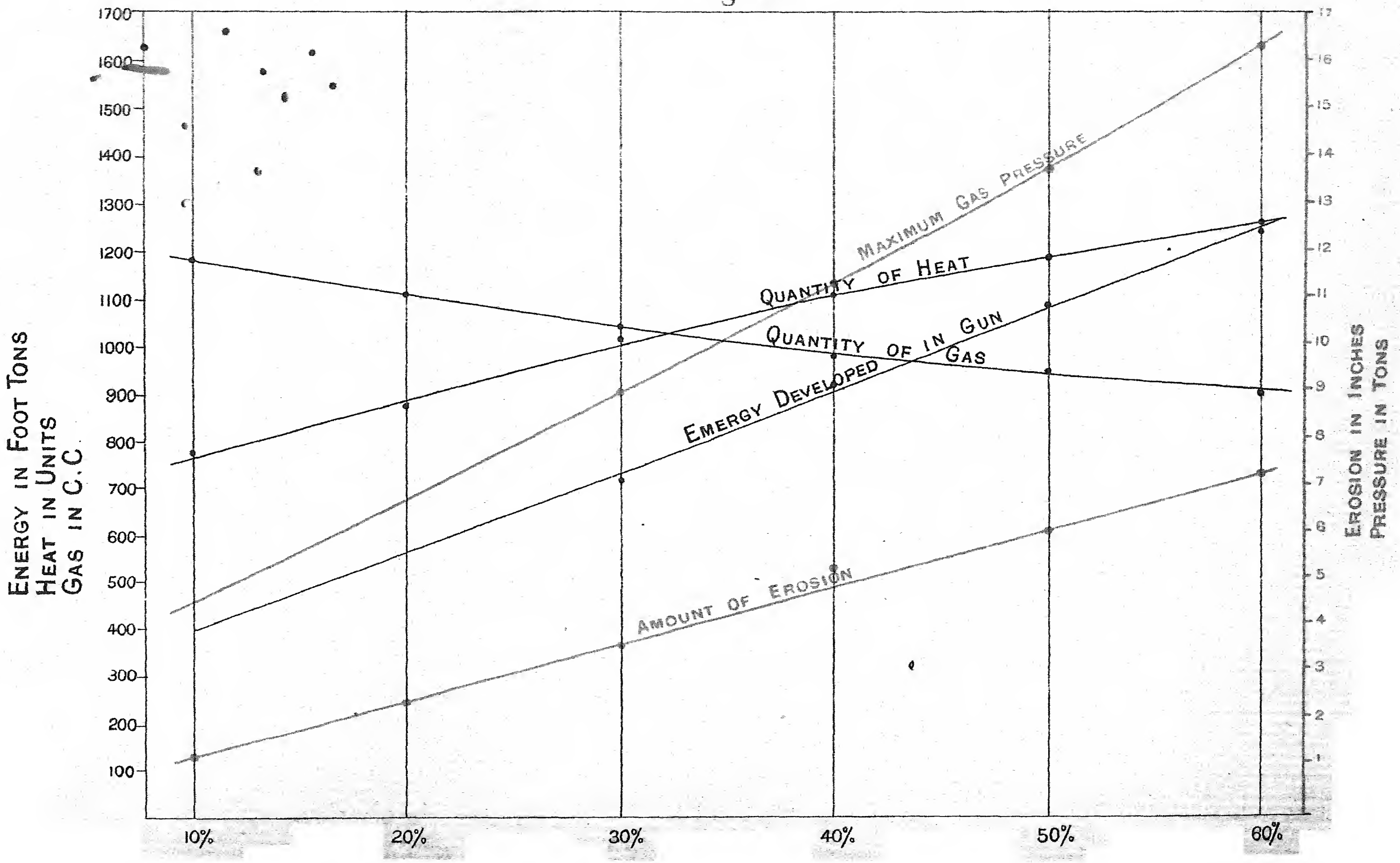
ploughed field. In the latter, the appearance is more as if the surface were washed away by the flow of the highly-heated gases.

But take it in what way you please, the heavy erosion of the guns of the service, if fired with the maximum charges, is a very serious matter, as with the large guns, accuracy and in a smaller degree energy, are rapidly lost after a comparatively small number of rounds have been fired.

Cordite was first produced for use in small arms only, where, owing to the small charges employed, the question of erosion is not of the same importance as with large guns; but its employment, from the great results obtained with it, was rapidly extended to artillery, and the attention of my friends, Sir F. Abel and Prof. Dewar, has for some time been devoted in conjunction with myself to investigating whether it is not possible materially to reduce this most objectionable erosion.

With this object I made the following series of experiments.

Fig VI.


Energy in Foot Tons
Heat in Units
Gas in C.C.
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
Maximum Gas Pressure
Quantity of Heat
Quantity of in Gun
Gas
Emergy Developed
Amount of Erosion
10%
20%
30%
40%
50%
60%
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Erosion in Inches
Pressure in Tons

I had cordite of the same dimensions prepared with varying proportions of nitro-glycerine and guncotton. The nitro-glycerine being successively in the proportions of 60, 50, 40, 30, 20, and 10 per cent., and with each of these cordites I determined the following points:—

1. The quantity of permanent gases generated.
2. The amount of aqueous vapour formed.
3. The heat generated by the explosion.
4. The erosive effect of the gases.
5. The ballistic energy developed in a gun, and the corresponding maximum pressure.
6. The capacity of the cordite to resist detonation when fired with a strong charge of fulminate of mercury.

The results of these experiments were both interesting and instructive.

To avoid wearying you with a crowd of figures, I have placed on Fig. VI. the results of the first five series of experiments.

On the axis of abscissæ are placed the percentages of nitro-glycerine, while the ordinates show the quantities of the gases generated, the amount of heat developed, the erosive effect of this explosive, the ballistic energy exhibited in a gun, and the maximum gaseous pressure.

You will note that with the smallest proportion of nitro-glycerine the volume of permanent gases is a maximum, and that the volume steadily decreases with the increase of nitro-glycerine. On the other hand, the heat generated as steadily increases with the nitro-glycerine, and if we take the product of the quantity of heat and the quantity of gas as an approximate measure of the potential energy of the explosive, the higher proportion of nitro-glycerine has an undoubted advantage; but in this case, as in the case of every other explosive with which I have experimented, the potential energies differ less than might be expected from the changes in transformation, as the effect of a large quantity of gas is to a great extent compensated by a great reduction in the quantity of heat generated.

This effect is, of course, easily explained, and was very strikingly exhibited in the much more complicated transformation experienced by gunpowders of different compositions, a long series of which were very fully investigated by Sir F. Abel and myself.

Looking at this diagram, you will have observed that the energy developed in the gun is very much smaller with the smaller proportions of nitro-glycerine, but if you will look at the corresponding

maximum-pressure curve you will note that the pressures have decreased nearly in like proportion. Hence it is probable that the lower effect is mainly due to a slower combustion of the cordite, and it follows that this effect may be, to a great extent, remedied by increasing the rate of combustion by reducing the diameter of the cordite to correspond with the reduction in the quantity of nitro-glycerine.

To test this point, I caused to be manufactured a second series of cordites of the same composition, but with the diameters successively reduced by ·03, as you see with the samples I hold, and this diagram (Fig. VII.) shows at a glance the result. The energies you see are roughly practically the same, but if you look at the pressure curve, you will observe that I have obtained a curve in which, on the whole, the pressures vary in the contrary direction, that is to say, in this case the pressures increase as the nitro-glycerine diminishes.

Taking the two series into account, they show that by a proper arrangement of amount of charge and diameter of cord, it would be possible to obtain the same ballistics and approximately the same pressure from any of the samples I have exhibited to you.

But I have to draw your attention to another point. From the curve showing the quantities of heat, you will note that in passing from 10 per cent. nitro-glycerine to 60 per cent., the heat generated has increased by about 60 per cent. But if you examine the curve indicating the corresponding amount of erosion, you will see that while the quantity of heat is only greater by about 60 per cent., the erosion is greater by nearly 500 per cent.

These experiments entirely confirm the conclusion at which I have previously arrived, viz., that heat is the principal factor in determining the amount of erosion.

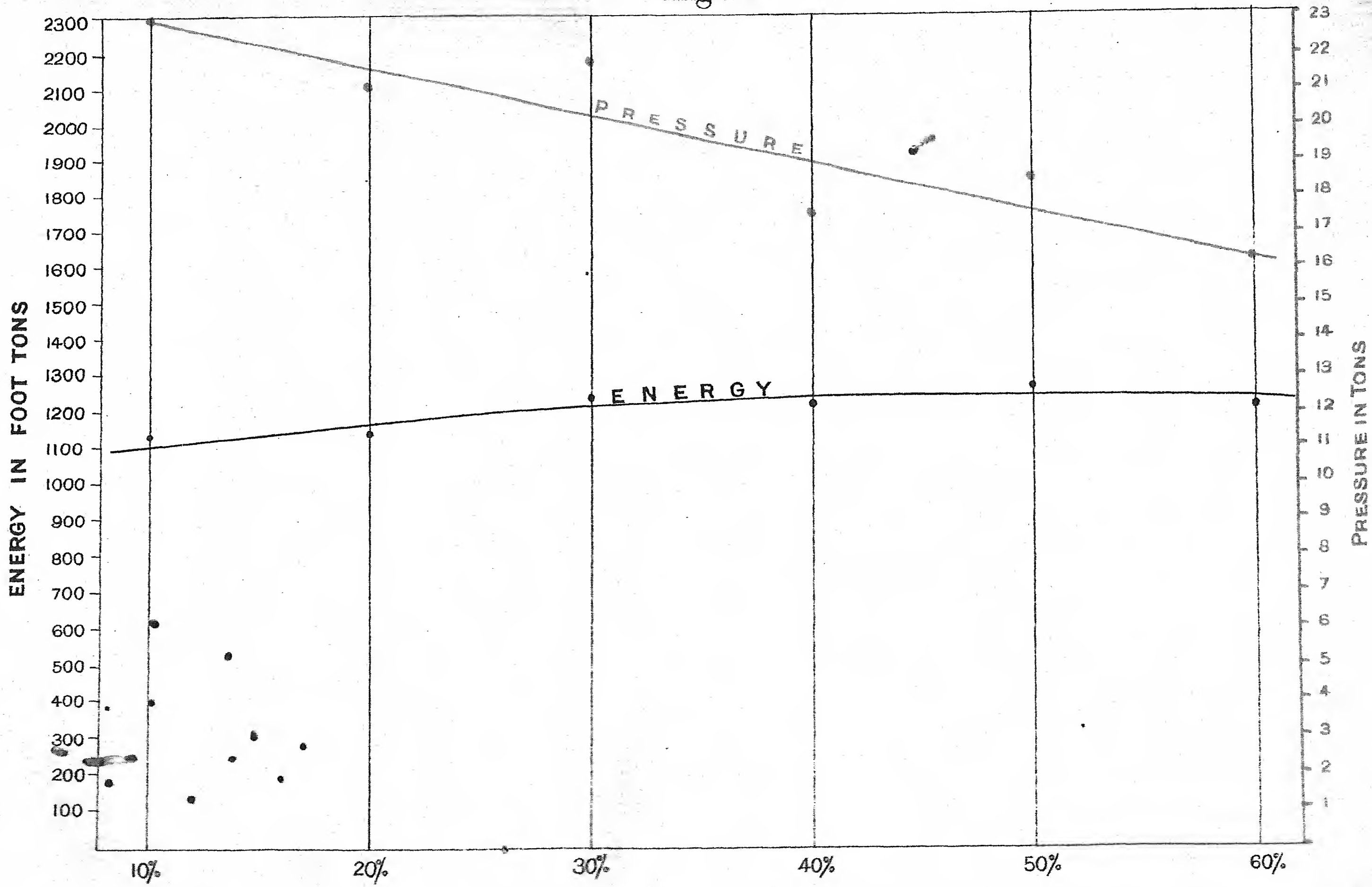
In experimenting with a number of alloys of steel, the greatest resistance was shown by an alloy of steel with a small proportion of tungsten, but the difference between the whole of these alloys amounted only to about 16 per cent.

The whole of these cordites were, as I have mentioned, subjected to detonation tests. None of them, so far as my experiments went, exhibited any special tendency in this direction.

I will now endeavour to describe to you a most interesting and important series of experiments, which I regret to say is still a long way from completion.

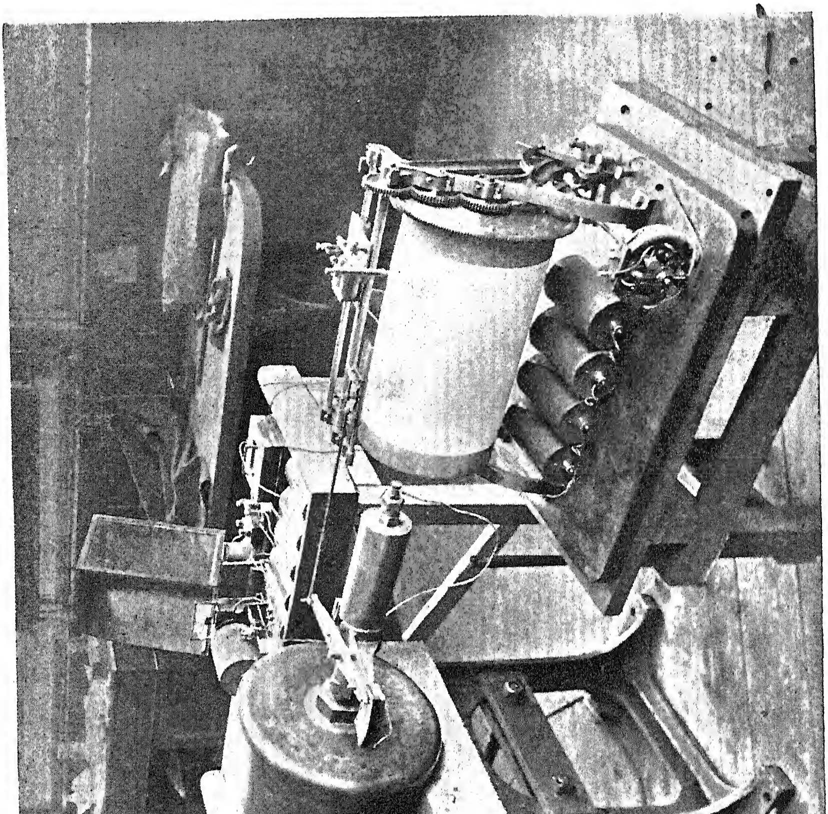
The objects of these experiments were—(1) to ascertain the time required for the combustion of charges of cordite in which the

Fig. VII.



ENERGY IN FOOT TONS
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
PRESSURE
ENERGY
10%
20%
30%
40%
50%
60%
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
PRESSURE IN TONS

PLATE VII.



[To face p. 537.

cordite was of different thicknesses, varying from 0·05-inch to 0·6 of an inch; (2) the rapidity with which the explosives part with their heat to the vessel in which the charge is confined; and (3) to ascertain, if possible, by direct measurement, the temperature of explosion, and to determine the relation between the pressure and temperature at pressures approximating to those which exist in the bore of a gun, and which are, of course, greatly above any which have yet been determined.

As regards the first two objects I have named, I have had no serious difficulties to contend with; but as regards the third, I have so far had no satisfactory results, having been unable to use Sir W. Roberts-Austen's beautiful instrument, owing to the temperature at the moment of explosion being greatly too high—high enough indeed to melt and volatilise the wires of the thermo-junction.

I am, however, endeavouring to make an arrangement by which I hope to be able to determine these points when the temperature is so far reduced that the wires will no longer be fused.

The apparatus I have used for these experiments (see Plate VII.) is placed on the table. The cylinder in which the explosions were made is too heavy to transport here, but this photograph will sufficiently explain the arrangement. The charge I used is a little more than a kilogramme, and it is fired in this cylinder in the usual manner.

The tension of the gas acting on the piston compresses the spring and indicates the pressure on the scale here shown. But to obtain a permanent record, the apparatus I have mentioned is employed.

There is, you see, a drum made to rotate by means of a small motor. Its rate of rotation is given by a chronometer acting on a relay, and marking seconds on the drum, while the magnitude of the pressure is registered by this pencil actuated by the pressure-gauge I have just described.

To obtain with sufficient accuracy the maximum pressure, and also the time taken to gasify the explosive, two observations, that is two explosions, are necessary.

If the piston be left free to move the instant of the commencement of pressure, the outside limit of the time of complete explosion will be indicated; but on account of the inertia of the moving parts the pressure indicated will be in excess of the true pressure, and the excess will be, more or less, inversely as the time occupied by the explosion.

If we desire to know the true pressure, it is necessary to compress the gauge beforehand to a point closely approximating to the expected

pressure, so that the inertia of the moving parts may be as small as possible—the arrangement by which this is effected is not shown in the diagram, but the gauge is retained at the desired pressure by a wedge-shaped stop, held in its place by the pressure of the spring, and to the stop a heavy weight is attached—when the pressure is relieved by the explosion, the weight falls, and leaves the spring free to act.

I have made a large number of experiments with this instrument, both with a variety of explosives and with explosives fired under different conditions. Time will not permit me to do more than to show you on the screen three pairs of experiments to illustrate the effect of exploding cordite of different dimensions, but of precisely the same composition.

I shall commence with rifle cordite. In this diagram (Fig. VIII.), the axis of abscissæ has the time in seconds marked upon it, while the ordinates denote the pressures; and I draw your attention to the great difference, in the initial stage, between the red and the blue curves. You will notice that the red curves show a maximum pressure some $4\frac{1}{2}$ tons higher than that shown by the blue curve; but this pressure is not real, it is due to the inertia of the moving parts. The red and blue curves in a very small fraction of a second come together, and remain practically together for the rest of their course. The whole of the charge is consumed in something less than fifteen thousandths of a second.

In the case of the blue curve, the maximum pressure indicated is obtained in the way I have described, and is approximately correct—about 9 tons per square inch. The rapidity with which this considerable charge parts with its heat by communication to the explosion-vessel is very striking. In 4 seconds after the explosion the pressure is reduced to about one-half, and in 12 seconds to about one-quarter.

I now show you (Fig. IX.) similar curves for cordite 0·35-inch in diameter or about fifty times the rifle cordite section. Here you see that the time taken to consume the charge is longer. The effect of inertia is still very marked although much reduced. The true maximum pressure is a little over 8·5 tons, but after the first third of a second the two curves run so close together that they are indistinguishable.

Again you see the pressure is reduced by one-half in 4 seconds, and in a little more than 12 seconds again halved.

The last pair of curves I shall show you (Fig. X.) was obtained

Fig. VIII.

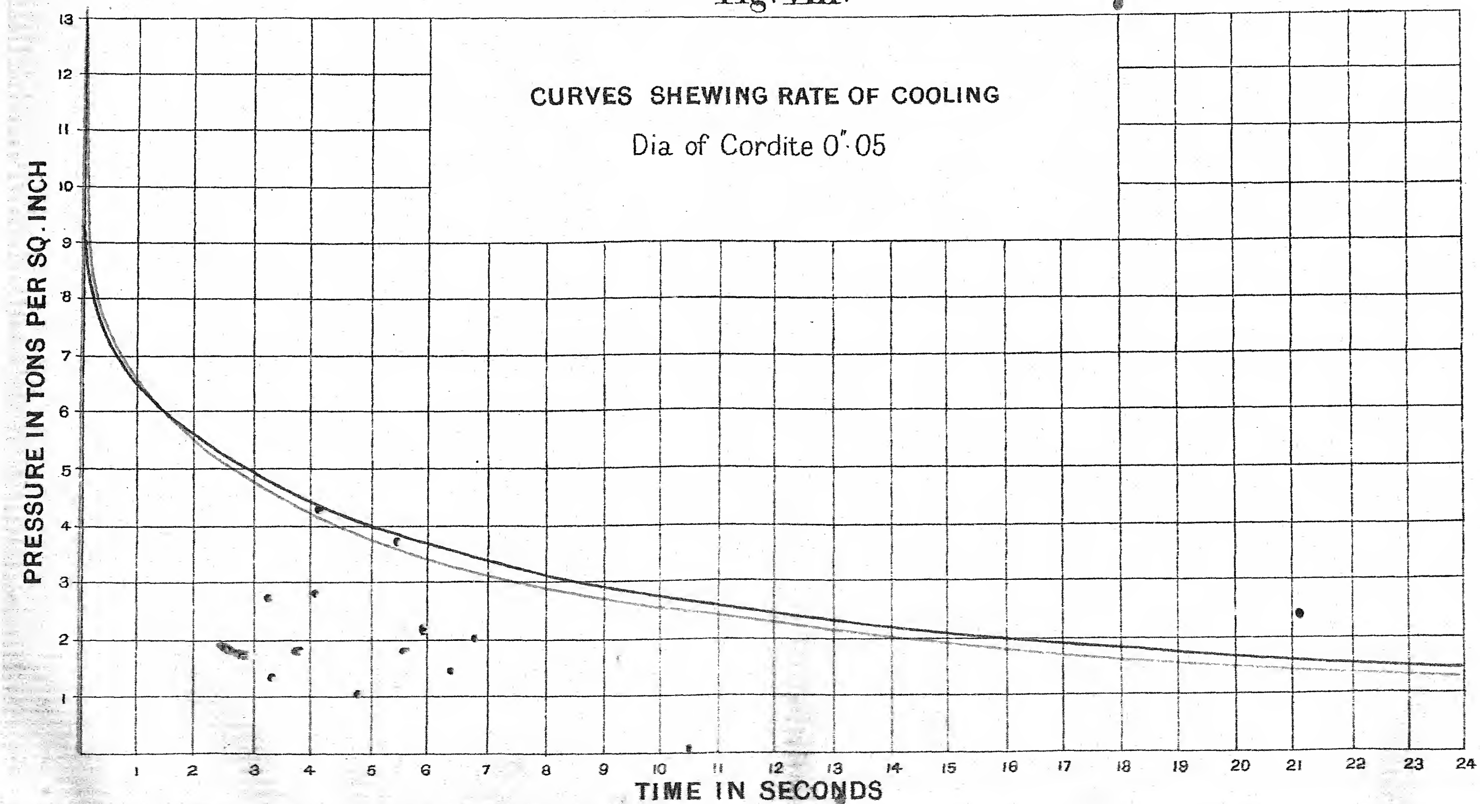

CURVES SHEWING RATE OF COOLING
Dia of Cordite 0".05
PRESSURE IN TONS PER SQ. INCH
TIME IN SECONDS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
1 2 3 4 5 6 7 8 9 10 11 12 13

Fig. IX.

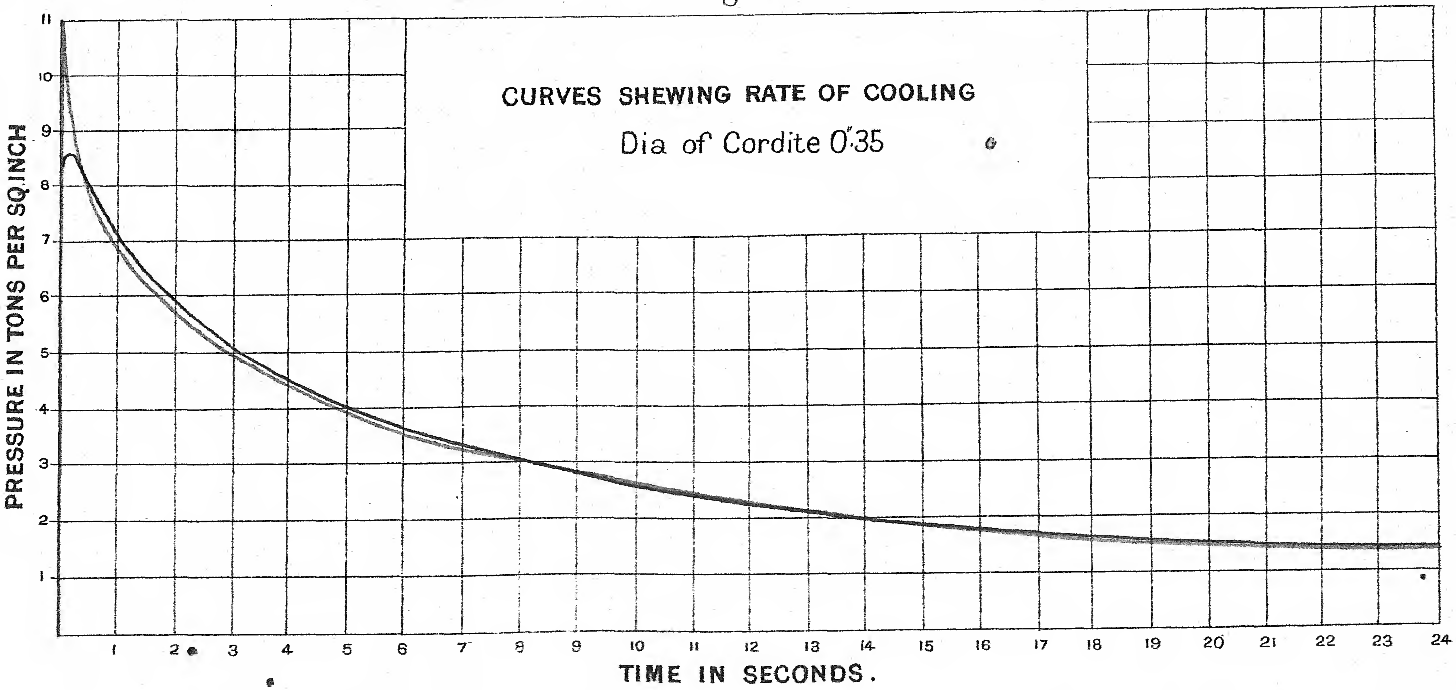
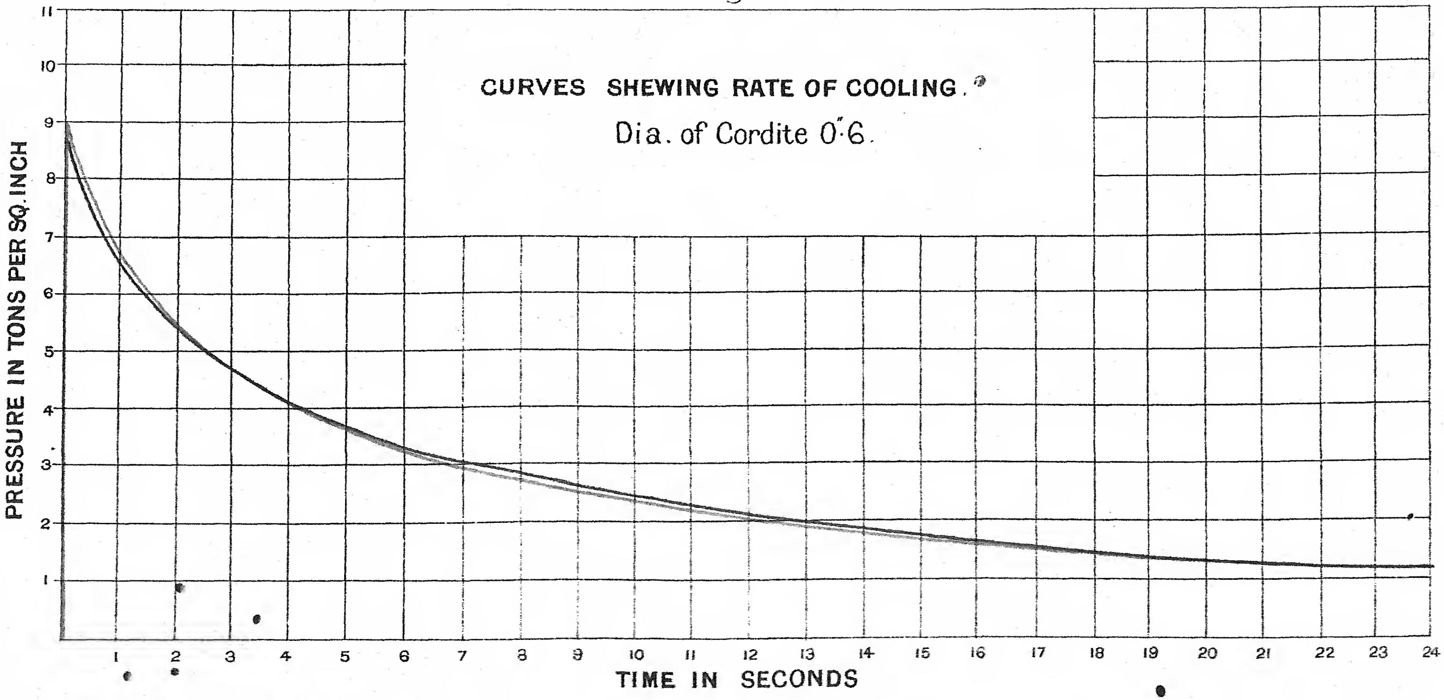

CURVES SHEWING RATE OF COOLING
Dia of Cordite 0".35
PRESSURE IN TONS PER SQ.INCH
TIME IN SECONDS.
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

Fig. X.



CURVES SHEWING RATE OF COOLING.
Dia. of Cordite 0"6.
PRESSURE IN TONS PER SQ. INCH
1
2
3
4
5
6
7
8
9
10
11
TIME IN SECONDS
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

with cordite 0·6-inch in diameter, or nearly 150 times the section of the rifle cordite. With this cordite the combustion has been so slow that the effect of inertia almost disappears; it is reduced to about half a ton per square inch. The maximum being nearly the same as in the last set of experiments. The time of combustion indicated I have called slow, but it is about ·06 of a second, and the whole of the experiments show a most remarkable regularity in their rate of cooling, the pressures at the same distance of time from the explosion being in all cases approximately the same, as indeed they ought to be. The density being the same and the explosive the same, the only difference being the time in which the decomposition is completed.

It appears to me that, knowing from the experiments I have described, the volume of gas liberated, its composition, its density, its pressure, the quantity of heat disengaged by the explosion; and knowing all these points with very considerable accuracy, we should be able, from the study of the curves to which I have drawn your attention, and which can be obtained from different densities of gas, to throw considerable light upon the kinetic theory of real, not ideal gases, at temperatures and pressures far removed from those which have been the subject of such careful and accurate research by many distinguished physicists.

The question, as I have said, involves some very considerable difficulties, nevertheless I am not without hope that the experiments I have been describing may, in some small degree, add to our knowledge of the kinetic theory of gas.

That wonderful theory faintly shadowed forth almost from the commencement of philosophic thought, was first distinctly put forward by Daniel Bernoulli early in the last century. In the latter half of the century now drawing to a close, the labours of Joule, Clausius, Clerk Maxwell, Lord Kelvin, and others, have placed the theory in a position analogous and equal to that held by the undulatory theory of light.

The kinetic theory has, however, for us artillerists a special charm, because it indicates that the velocity communicated to a projectile in the bore of a gun is due to the bombardment of that projectile by myriads of small projectiles moving at enormous speeds, and parting with the energy they possess, by impact, to the projectile.

There are few minds which are not more or less affected by the infinitely great and the infinitely little.

It was said that the telescope, which revealed to us infinite space,

was balanced by the microscope, which showed us the infinitely small; but the labours of the men to whom I have referred, have introduced us to magnitudes and weights infinitesimally smaller than anything that the microscope can show us, and to numbers which are infinite to our finite comprehension.

Let me draw your attention to this diagram (Fig. II.)* showing the velocity impressed upon the projectile, and let me endeavour to describe the nature of the forces which acted upon it to give it its motion. I hold in my hand a cubic centimetre, a cube so small that I daresay it is hardly visible to those at a distance. Well, if this cube were filled with the gases produced by the explosion at 0° C. and atmospheric pressure, there would be something over seven trillions, that is, seven followed by eighteen cyphers, of molecules. Large as these numbers are, they occupy but a very small fraction of the contents of the cubic centimetre, but yet their number is so great that they would, if placed in line touching one another, go round many times the circumference of the earth, a pretty fair illustration of Euclid's definition of a line.

These molecules, however, are not at rest, but are moving, even at the low temperature I have named, with great velocity, the molecules of the different gases moving with different velocities dependent upon their molecular weight. Thus, the hydrogen molecules which have the highest velocity move with about 5500 feet per second mean velocity, while the slowest, the carbonic anhydride molecules, have only 1150 feet per second mean velocity, or about the speed of sound.

But in the particular gun under discussion, when the charge was exploded there were no less than 20,500 c.c. of gas, and each centimetre at the density of explosion contained 580 times the quantity of gas, that is, 580 times the number of molecules that I mentioned. Hence the total number of molecules in the exploded charge is 8⅓ quadrillions, or, let us say, approximately for the total number, eight followed by twenty-four cyphers.

It is difficult for the mind to appreciate what this immense number means, but it may convey a good idea if I tell you that if a man were to count continuously at the rate of three per second, it would take him 265 billions of years to perform the task of counting them.

So much for the numbers; now let me tell you of the velocities with which, at the moment of explosion, the molecules were moving. Taking first the high-velocity gas, the hydrogen, the molecules of the

* See p. 527.

gas would strike the projectile with a mean velocity of about 12,500 feet per second. You will observe, I say, mean velocity, and you must note that the molecules move with very variable velocities. Clerk Maxwell was the first to calculate the probable distribution of the velocities. A little more than one-half will have the mean velocity or less, and about 98 per cent. will have 25,000 feet per second or less. A very few, about one in 100 millions, might reach the velocity of 50,000 feet per second.

The mean energy of the molecules of different gases at the same temperature being equal, it is easy from the data I have given to calculate the mean velocity of the molecules of the slowest moving gas, carbonic anhydride, which would be about 2600 feet per second.

I have detained you, I fear, rather long over these figures, but I have done so because I think they throw some light upon the extraordinary violence that some explosives exhibit when detonated. Take, for instance, the lyddite shell exploded by detonation I showed you earlier in the evening. I calculate that that charge was converted into gas in less than the one 60,000th part of a second, and it is not difficult to conceive the effect that these gases of very high density suddenly generated, the molecules of which are moving with the velocities I have indicated, would have upon the fragments of the shell.

The difference between the explosion of gunpowder fired in a close vessel and that of guncotton or lyddite when detonated, is very striking. The former explosion is noiseless, or nearly so. The latter, even when placed in a bag, gives rise to an exceedingly sharp metallic ring, as if the vessel were struck a sharp blow with a steel hammer.

But I must conclude. I began my lecture by recalling some of the investigations I described in this place a great many years ago. I fear I must conclude in much the same way as I then did, by thanking you for the attention with which you have listened to a somewhat dry subject, and by regretting that the heavy calls made on my time during the last few months have prevented my making the lecture more worthy of my subject and of my audience.

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